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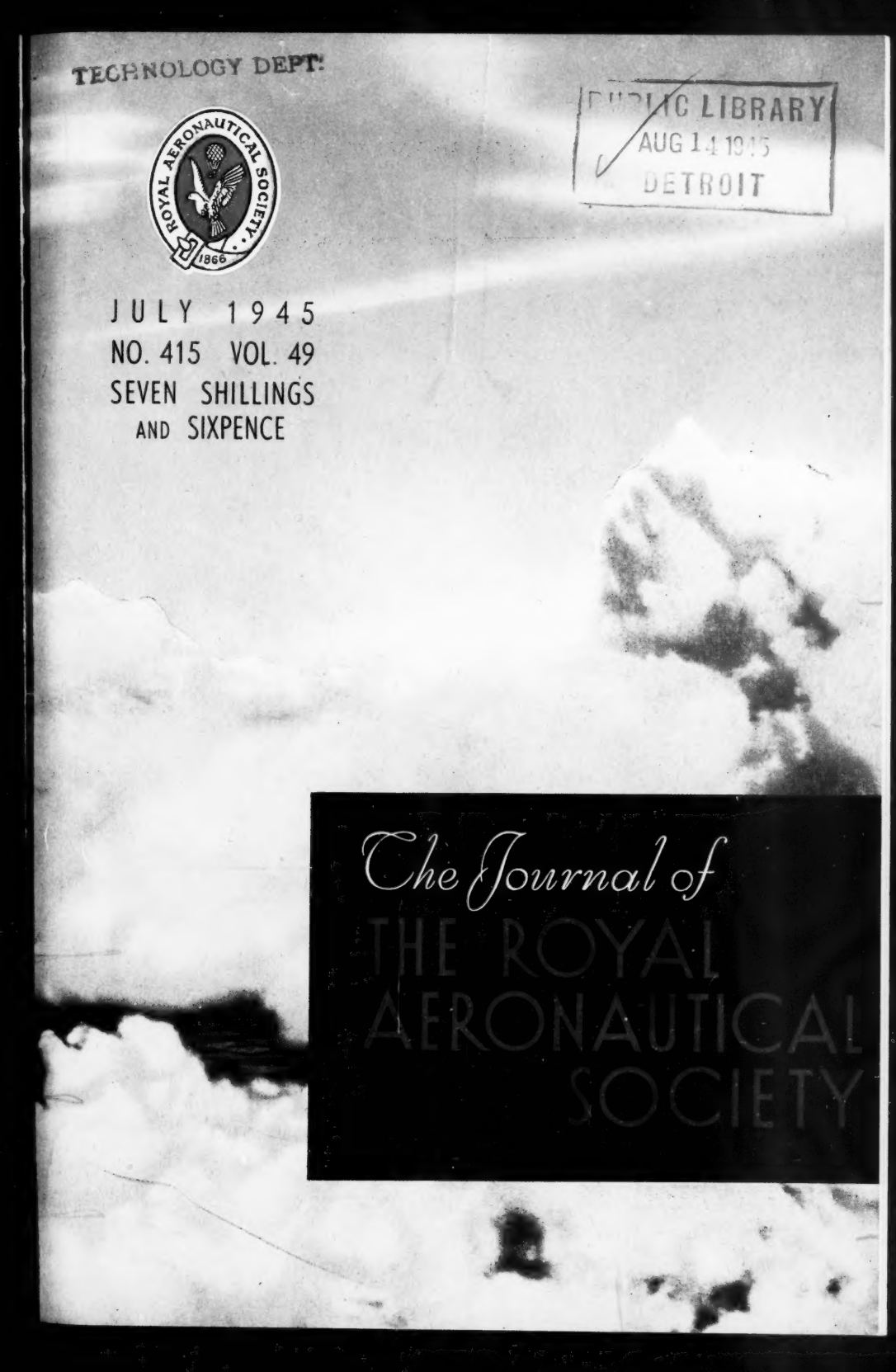

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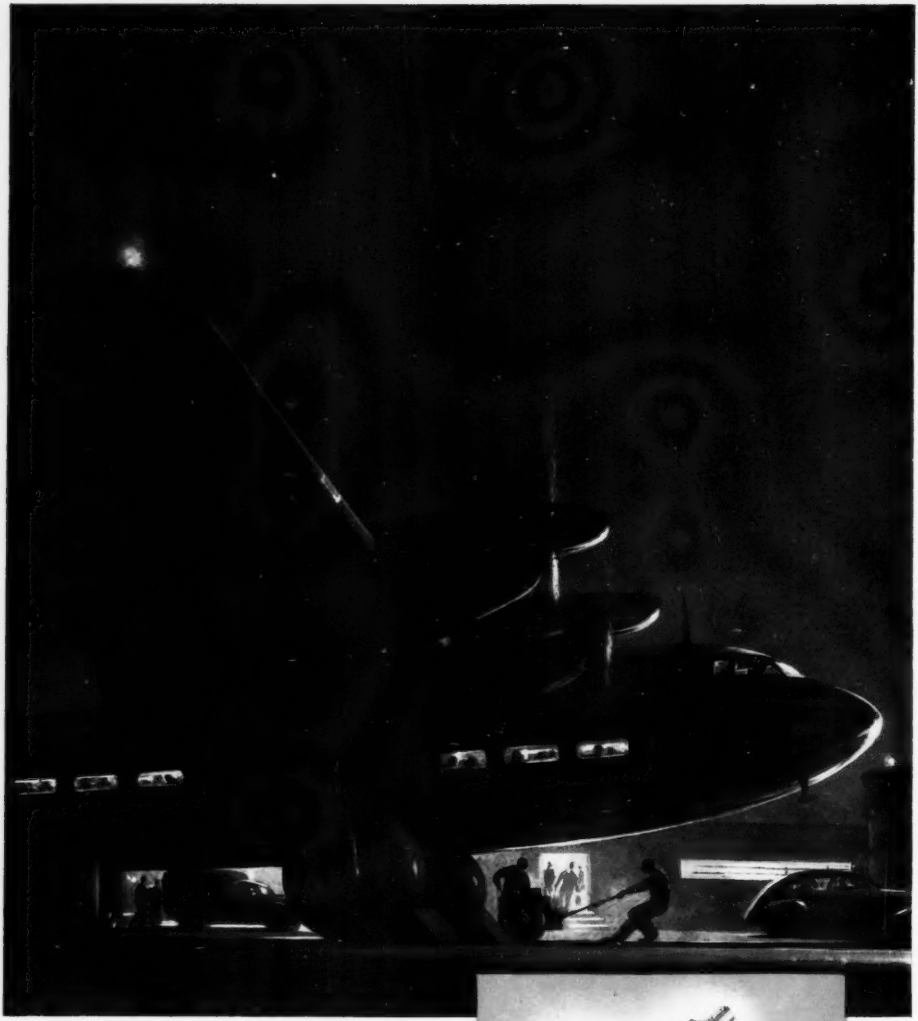

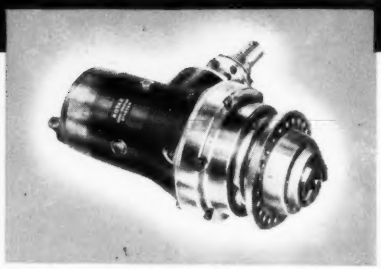

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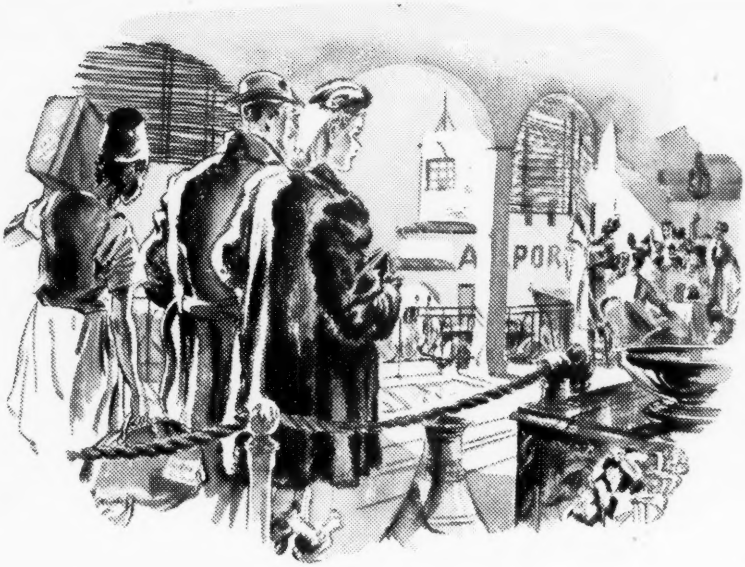

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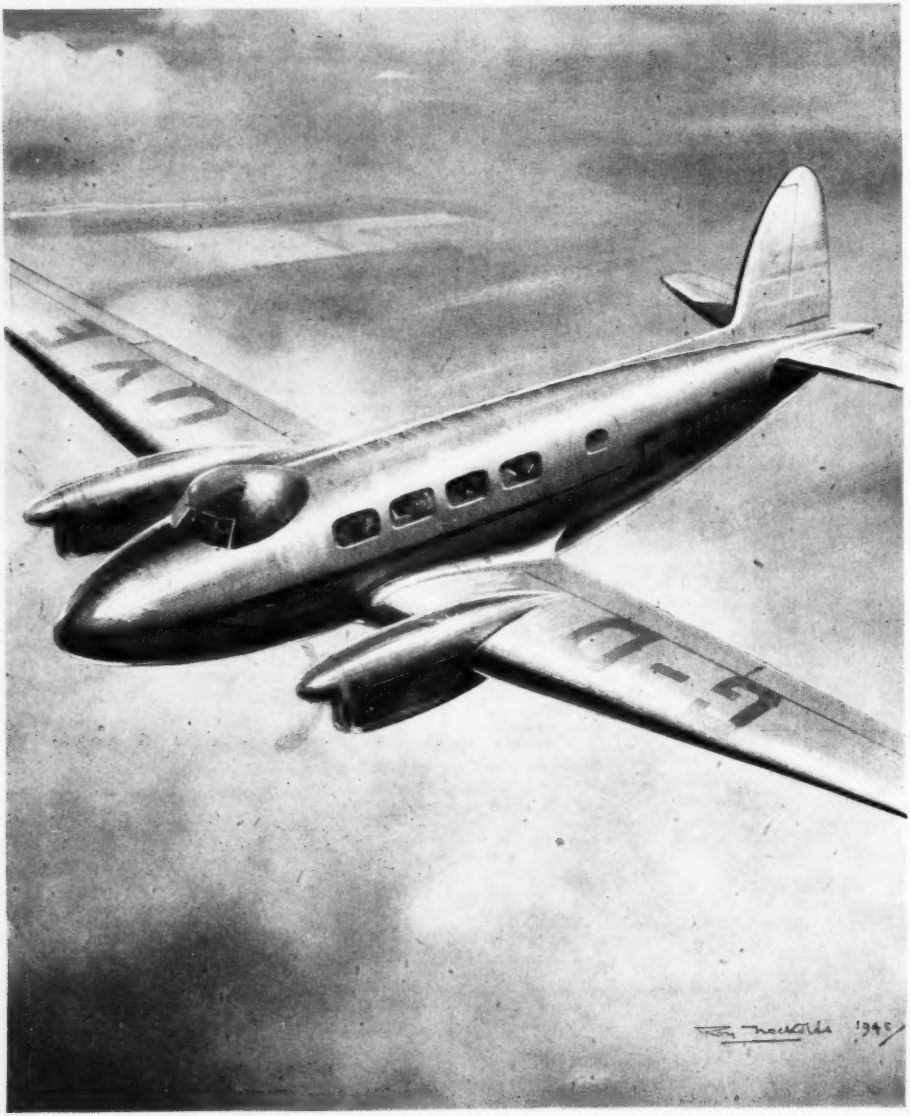

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THE SOCIETY'S PRIZES

The Society offers a number of valuable prizes, most of them annually. Full particulars of the conditions attaching to the awards of these prizes may be obtained on application

Society's Gold Medal

This is the highest honour which the Society can confer for work of an outstanding or fundamental nature in aeronautics.

British Gold Medal for Aeronautics

The British Gold Medal for Aeronautics is awarded for an achievement leading to advancement in aeronautical science.

Simms Gold Medal

The Simms Gold Medal is awarded annually for the best paper read in any year before the Society on any science allied to aeronautics, e.g., meteorology, wireless telegraphy, instruments.

The George Taylor (of Australia) Gold Medal

The Taylor Gold Medal is awarded annually, at the discretion of the Council, for the most valuable paper submitted or read during the previous session.

Wakefield Gold Medal

The Wakefield Gold Medal is awarded annually to the designer of any invention or apparatus tending towards safety in flying, and is open to members or non-members.

Society's Silver Medal

The Society's Silver Medal is awarded, at the discretion of the Council, for some advance in aeronautical design.

British Silver Medal for Aeronautics

The British Silver Medal for Aeronautics is awarded for an achievement leading to advancement in aeronautical science.

Society's Bronze Medal

The Society's Bronze Medal is awarded, at the discretion of the Council, under the same conditions as those for the Silver Medal, but for some less important advance in aeronautical design.

Wilbur Wright Memorial Premium

The Wilbur Wright Memorial Lecture is held annually, a premium of fifty pounds being awarded to the lecturer invited by the Council to deliver the lecture. The lecture is usually given alternately by an American and an Englishman, and is the most important aeronautical lecture of the year. It is delivered whenever possible, on the last Thursday in May of each year.

British Empire Lecture

The Council of the Royal Aeronautical Society have completed the arrangements for the founding of a British Empire Lecture.

The lecture, on any aeronautical subject approved by the Council, will be delivered annually in September in London, by a lecturer, chosen in alternate years from the British Dominions and Colonies and Great Britain.

The Council, by founding this British

Empire Lecture, are anxious to encourage new ideas and new points of view from all parts of the British Empire, and to make the Lecture second only in importance to the Wilbur Wright Memorial Lecture.

The British Empire Lecture will have a premium of £50 attached to it, and in the case of lecturers coming from the Dominions and Colonies an allowance up to £100 will be paid towards the Lecturer's expenses.

It is proposed to hold the first lecture in September, 1945, and suggestions for lecturers should be received by May 31st, 1945, at the latest.

R.38 Memorial Prize

The R.38 Memorial Prize is offered annually for the best paper received by the Society on some subject of a technical nature in the science of aeronautics, preference being given to papers which relate to airships. The prize is twenty-five guineas.

The Herbert Akroyd Stuart Lectures

Under the will of the late Mr. Herbert Akroyd Stuart a sum of £700 is held in trust by the Society for the offer of a prize every two years, for the best paper or lecture read or given before the Society dealing with the Origin and Development of Heavy-oil Aero Engines. The prize is open to members and non-members.

Edward Busk Memorial Prize

The Edward Busk Memorial Prize is offered annually for the best paper received by the Society on some subject of a technical nature in connection with aeroplanes (including seaplanes). Its value is twenty guineas.

Pilcher Memorial Prize

The Pilcher Memorial Prize is offered annually, at the discretion of the Council, for the best paper by a Student on heavier-than-air craft or any analogous subject. Its value is five guineas.

Usborne Prize

The Usborne Prize is offered annually, at the discretion of the Council, for the best paper by a Student on some subject in connection with Aero Engines. Its value is five guineas.

Major Baden-Powell Memorial Prize

The Major Baden-Powell Memorial Prize is awarded in May and December of each year to the student who is considered the best student by the examiners in the Society's Association Fellowship examinations. Its value is three guineas.

Elliott Memorial Prize

The Elliott Memorial Prize is awarded twice yearly to the apprentice at Halton who has the highest percentage of marks in the passing-out examination. Its value is 2½ guineas for each award.

R. P. Alston Memorial Prize

The R. P. Alston Memorial Prize is awarded to any Graduate or Student of the Society for work done leading to improvement in the safety of aircraft, and particularly for improvement in stability and control. Its value is approximately £5.

Branch Prize

The Council offer an annual prize of twenty guineas for the best paper read before the Branches during the previous lecture Session. The prize is open to any member of the Society or of any Branch.

Journal Premium Awards

The Council has set aside an annual sum of £250 to be given as premium awards to authors of papers published in the Journal.

AN APPRECIATION

The Council of the Royal Aeronautical Society wish to thank those Companies who, by their generous co-operation, have done so much to help in the production of the Journal in its new form.

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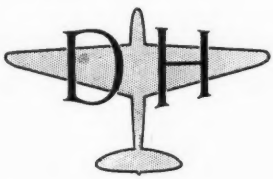

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The Journal of The Royal Aeronautical Society was founded in 1897 in succession to the Annual Reports. For the opinions expressed in Papers that are signed or initialled the authors alone are responsible. None of the papers or paragraphs must be taken as expressing the opinion of the Council of The Royal Aeronautical Society unless such is definitely stated to be the case. **The Journal is published monthly at the Offices of the Society, 4, Hamilton Place, Piccadilly, London, W.1.** Subscriptions per annum, £4 10 0 post free; Single Numbers 7 6 or 7/9 post free. All communications for publication in the Journal, or on general matters affecting the Society should be addressed to—The Secretary, J. Laurence Pritchard, 4, Hamilton Place, W.1. The Society's Bankers are Messrs. Coutts and Co. All communications respecting Advertisement matters should be addressed to—The Advertisement Manager, Journal of The Royal Aeronautical Society, 4, Hamilton Place, W.1.

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JULY NOTICES 1945

JOURNAL PREMIUM AWARDS

The Council have set aside an annual sum of £250 for the award of premiums for papers published in the *Journal* and the Council hope that members will contribute papers on their own special subjects.

Contents of the July Journal

Hydraulics for Aircraft, by R. H. Bound.

Some Notes on Vibration Analysis, by R. J. Manley.

Editor of the Journal

Applications are invited for the post of Editor of the Journal and other publications of the Society. Please give full particulars of experience, etc., to the Secretary.

Librarian

A vacancy occurs at the Society for a full-time Librarian. A knowledge of German and French and technical knowledge would be an advantage. Those interested should apply in writing to the Secretary.

Lectures

A full lecture programme is being prepared and will be sent to all members as soon as possible.

DERBY BRANCH

Lectures by the following have been arranged and will be held in the Rolls-Royce Welfare Hall, Nightingale Road, Derby:—

September 3rd—Lord Brabazon of Tara, M.C., P.C., F.R.Ae.S. (Past-President of the Society).

October 1st—Dr. H. Roxbee-Cox, B.Sc., D.I.C., F.R.Ae.S. (Chairman, Power Jets, Ltd.).

November 5th—Air Commodore Vernon Brown, C.B., O.B.E., M.A., F.R.Ae.S., and Wing Commander N. G. Bennett, M.B.E. (Air Ministry Accidents Investigation Branch).

December 3rd—Annual General Meeting.

Election of Members

The following members were recently elected:—

Associate Fellows

Jack Ball (from Graduate), Jack Charles Barrett, Richard Lamport Bennetts, Bernard Horace Becker (from Associate), Michael Blaicher, William Thomas Blanchard, Harold Cecil Brazier, Walter George Bushell, Frank Cross, Wilfrid Dancy, Kenneth Roy Davies (from Graduate), John Ernest Patrick Dunning, Norman Kempton Dyson (from Associate), Stephen Arthur Embley, Emrys Richard Evans, Thomas Kenneth Garrett (from Graduate), Jack Grant (from Graduate), Kenneth Calvert Hales (from Graduate), Denys Chambers Hope (from Graduate), Arthur Percival Hunt (from Associate), Kenneth Charles Hunt, John Jewell, William John Killops, Thomas Alfred Kirkup, Peter George Gradwick Knight (from Graduate), Albert Frederick Le Maistre, Leslie William Meyer, John Mullin (from Student), Jerzy Ploszajski, Cyril Rapley, Henry Arthur Reed, Stanislaw Jojciech Rogalski, James Spinks, Golda Sztern (from Graduate), Howell Henry Beaumont Morris Thomas,

Alexander Tupalski, Derek Victor Wordsworth (from Graduate), Alan Yarker, Alec David Young, Henry James Webb.

Baden-Powell Memorial Prize

The Baden-Powell Memorial Prize has been awarded to Mr. W. Spence, who was considered by the Examiners to be the best candidate in the May, 1945, Associate Fellowship Examinations.

Associates

Colin Gillatt Britten, Leslie Ernest Bishop (from Student), Norman Bell Bruce, John Frank Pogmore Cobb, Archibald Cooke, Cyril Davies, William Leslie Webley Davies, Cecil Dean, Richard Dyrgalla, Samuel Eric Esler, Albert Leslie Fearne, Lionel Furnival, Trevor Harold Gilbert (ex-Student), Maurice Hugh Charles Gordon, James Douglas More Gray, Konstanty Gutowski, Edward Cecil Howes, John Robert James Alexander Lowes, James McCorquodale Lyall, Henry Frederick Peel, Harry Proctor Powell, Reginald Harold Rout, Basil Sinclair, David Arthur Smith, James Smith, John Rhys Sully, Geoffrey Herbert Thomas, Alan Waller, Tom Wharton, Stanley Anderson Wharrier, Norman Russell Whyatt, Geoffrey Norman Young.

Graduates

Robert Ernest Agar (from Student), Kenneth Arthur Joseph Foord, Derek James Hardy (from Student), Digby Kenneth Harris (from Student), William Geoffrey Heath (from Student), Leslie Maidment (from Student), William Mongar, Francis Joseph Newton, Brian Sutcliffe, Derrick Edward Joseph Tipping (from Student).

Students

Stuart Alexander Andrews, William Alexander Beedie, Malcolm Keith Bowden, Michael Laurence Camp, Thomas Dorian Robertson Carroll, Edward James Cosgrove, Stanley Andrew Edward Griffiths, Eric Dorian King, Herbert Richard Leather.

Companions

John James Lister, David Norman Owen, Blaid Dudley Richardson.

Associate Fellowship Examinations

The following candidates were successful in the May, 1945, Associate Fellowship Examinations:—

Allen, W. J., Applied Mechanics; Anderson, J. A., Design (Aero Engines); Bowles, F. G. K., Pure Mathematics; Briginshaw, G. F., Pure Mathematics, Theory of I.C. Engines, Design (Aero Engines); Budden, P. A., Pure Mathematics; Castle, R. P., Pure Mathematics; Chaplin, N. J. E., Strength of Aeronautical Materials; Chapman, C. A., Pure Mathematics, Strength of Aeronautical Materials, Theory of Machines; Conea, M. M., Aerodynamics; Conway, A., Strength of Aeronautical Materials, Design (Aircraft); Curzon, A. J., Aircraft Materials; Ebershardt, P. C. V. R., Aerodynamics; Fairbrother, A., Pure Mathematics; Glasspole, M. A., Strength of Aeronautical Materials; Green, P. R., Air Transport; Grigg, R. E., Pure Mathematics; Guttridge, J. C., Applied Mathematics; Hatton, C. D., Strength of Aeronautical Materials (1st place); Hellier, E. J., Strength of Aeronautical Materials; House, M. L., Aircraft Materials; House, T. A., Pure Mathematics; Kendall, R., Applied Mathematics; Kennedy, G. A., Theory of Machines; Levey, E. D. R., Applied Mathematics; Marek, H., Pure Mathematics; Meiklem, P., Pure Mathematics, Strength of Materials, Aerodynamics; Mead, D. J., Pure Mathematics (1st place), Strength of Aeronautical Materials; Moorman, O. B. R., Pure Mathematics; Mulholland, C. A., Air Transport (1st place); Namjoshi, M. V., Pure Mathematics, Aircraft Materials (1st place); Nerriere, Q. H. M., Theory of I.C. Engines; Palmer, E. N., Applied Mathematics, Navigation and its application to Aeronautics; Ricketts, G. C., Pure Mathematics; Robertson, F. H., Pure Mathematics;

Robertson, I. W. C., Strength of Aeronautical Materials, Design (Aircraft); Saravanos, B., Design (Aircraft) (1st place); Saunders, G. C., Pure Mathematics; Smith, B. L., Applied Mathematics; Smith, S. J., Design (Aircraft), Applied Mathematics (1st place); Spence, W., Applied Mathematics, Theory of I.C. Engines (1st place), Theory of Machines (1st place); Stanley, G., Applied Mathematics, Theory of I.C. Engines; Starr, E. V., Theory of I.C. Engines, Design (Aero Engines) (1st place); Todd, F., Applied Mathematics, Aerodynamics, Design (Aircraft); Vowles, E. J. M., Pure Mathematics; Miss M. Ward, Theory of Machines; Weiss, E. J., Applied Mathematics; Wimpenny, J. C., Applied Mathematics, Strength of Aeronautical Materials, Aerodynamics.

Additions to Library

Pamphlets in italics with location reference following in brackets. Books marked * may not be taken out on loan.

B.a.335.—*Convair's RY-3 (Press release, stencil). Consolidated Vultee Corp.*, 1945. (Y.3.ii.C.)

B.b.23.—*The Response of Helicopters with Articulated Rotors to Cyclic Blade Pitch Control. A. F. Donovan and M. Goland. Article in J. Aeron. Sciences, October*, 1944. (*Photostat.*) (Y.1.b.14.)

D.b.233.—Civil Aviation and Peace. J. Parker Van Zandt. Brookings Institution (Washington), 1944. $1 (5/-).

D.b.234.—*Our Future in the Air. G. Russell Vick Committee. Liberal Publication Dept.*, 1945. 6*d*. (PD.2.b.8.)

E.b.105.—*The History of Structural Testing. A. G. Pugsley. Article in "The Structural Engineer," December*, 1944. (PE.1.b.4.)

E.b.106.—*Simplified Analysis of Hollow Beams with Longitudinal Webs subjected to Torsional Loads. Eryk Kosko. (Reprint from "J. Aeron. Sciences," January*, 1945.) (Y.8.a.25.)

*G.b.4.—*British Standards Institution Specification 3T.51: High Pressure Seamless Copper Tubes*, 1945. 1/-. (File Case.)

H.b.88.—*Legal Rules for International Aviation. Charles S. Rhyne. Reprint from "Virginia Law Review," March*, 1945. (PH.1.b.8.)

J.g.208.—Introduction to Meteorology. Sverre Petterssen. McGraw Hill, 1941. 15/-.

J.g.209.—Weather Analysis and Forecasting. Sverre Petterssen. McGraw Hill, 1940. 30/-.

J.g.210.—Dynamic Meteorology. J. Holmboe, G. E. Forsythe and Wm. Gustin. John Wiley (N.Y.) or Chapman & Hall (London). 1945. $4.50.

J.g.211.—*Smithsonian Miscellaneous Collection, Vol.* 104, *No.* 9: *On the* 27,0074-*Day Cycle in Washington Precipitation. C. G. Abbot.* 1945. (Y.30.i.)

*L.d.107.—Air Navigation (A.P.1234). H.M.S.O., 1944. 7/6.

L.j.94.—Essentials of Aerial Surveying and Photo Interpretation. Talbert Abrams. McGraw Hill. 1944. 18/-.

L.k.47.—The Biology of Flight. F. L. Fitzpatrick and K. A. Stiles. G. Allen & Unwin, 1944. 8/6.

M.a.29.—Aircraft Electrical Engineering. Randolph Matson. McGraw Hill, 1943. 21/-.

M.c.68.—Aircraft Radio and Electrical Equipment. H. K. Morgan. Pitman Publishing Corp., 1941. 22/6.

Q.b.77.—Report of Proceedings of 19th A.S.L.I.B. Conference, 1944. 6/-.

*R.b.259.—*Comparative Table: Balloon and Danilewsky Flying-Apparatus. K. Danilewsky.* (*Privately printed at Charkov*, 1898.) (Y.11.i.12a.)

S.c.15.—*French Air Force*, 1940-44. *Lt.-Col. R. Gaujour.* (*Official, French Air Forces in England.*) 1945. (Y.9.F.)

T.c.43.—*Mr. Andrée's Balloon Voyage to the North Pole. Article by A. T. Story. "Strand" Magazine,* 1896. (PT.2.b.3.)

*UU.c.—*National Advisory Committee for Aeronautics, U.S.A., Technical Memoranda*:—

No. 1067: The Minimum Energy Loss Propeller. N. Poliakhov. (C.A.H.I. No. 455, 1939.)

No. 1069: The Friction of Piston Rings. H. W. Tischbein. (Kraftstoff, 1939-40.)

No. 1076: New Method of Determining the Polar Curve of an Aeroplane in Flight. B. N. Yegorov. (C.A.H.I. No. 418, 1939.)

No. 1077: Calculation of Centrally Loaded Thin-Walled Columns above the Buckling Limit. F. Reinitzhuber. (L.F.F., July, 1942.)

No. 1080: A New Apparatus for Measuring the Temperature at Machine Parts Rotating at High Speed. E. Gnam. (Motortechnische Z., October, 1943.)

J. Laurence Pritchard,
Secretary.

HYDRAULICS FOR AIRCRAFT

by

R. H. Bound, F.R.Ae.S., F.S.E., M.I.M.E., A.M.I.A.E.

Mr. Bound is the Technical Director of Dowty Equipment Co. He has had considerable experience in aircraft design, having worked with Hawker Aircraft Co., A. V. Roe, and Percival Aircraft Co. He was elected a Fellow of the Society in November, 1941.

A MEETING of the Society was held in the Lecture Hall of the Institution of Mechanical Engineers, Storey's Gate, St. James's Park, Westminster, London, S.W.1, on Thursday, March 22nd, 1945, at which a paper by Mr. R. H. Bound, F.R.Ae.S., F.S.E., M.I.M.E., A.M.I.A.E., on "Hydraulics for Aircraft," was read and discussed. In the chair, the President, Sir Roy Fedden.

THE CHAIRMAN: It was a great pleasure to welcome Mr. R. H. Bound, a Fellow of the Society, who was to present a paper on "Hydraulics for Aircraft." A fortnight ago a paper was read by Mr. Woodford, an Associate Fellow of the Society, who was in the opposite camp, and one of the main protagonists of electrics. With Mr. Woodford's views still fresh in their minds, he believed there would be a good discussion on Mr. Bound's paper. From the very earliest days, Mr. Bound had been with Mr. Dowty and for the last 9 years had been in charge of the technical direction and design for the Dowty Equipment Co. He had had considerable experience of aircraft design, having been first with the Hawker Co. for a number of years. Then for 7 or 8 years he had been with the Avro Co. and just before joining Dowty's he was chief draughtsman of the Percival Co. Thus Mr. Bound had had wide experience of aircraft design and therefore should know what the user required in hydraulics. He felt it would be right to say that Mr. Bound felt there was a use for both hydraulics and electrics in the ancillary equipment of aircraft and that he also had very definite views as to how the two should be applied.

Paper received March, 1945.

Mr. R. H. BOUND (Fellow): In this paper I shall confine my remarks to power operated services other than gun turrets.

It may not be out of place to open this lecture with a general review of the four means of operating aircraft power services, these are:—

(1) Pneumatic;
(2) Mechanical;
(3) Hydraulic;
(4) Electric.

Fundamentally it is necessary to take energy from the aero engine and convert it for operating the various services.

The aero engine is a high speed unit, but the services are operated comparatively slowly. Thus an undercarriage which completes an angular movement of approximately 90° in 5 seconds has a mean speed of 3 r.p.m.

compared with the engine speed of say 3,000 r.p.m.

Pneumatic systems cannot compete with hydraulic power services to meet heavy loading as air compressors cannot generate pressures approaching those of hydraulic pumps which can operate at 3,000 lb./sq. inch. The use of pneumatics would lead to bulkier and heavier equipment. On the other hand, for such services as the operation of wheel brakes, and in some instances, the actuation of bomb doors, where it is necessary to obtain what is termed "winking" operation, *i.e.*, rapid action, pneumatics can be used with advantage.

Mechanical operation can be achieved by rods (torsion or push and pull) or flexible shaft drives, but the practical difficulties are considerable, also the reduction gearing is complicated and heavy.

The greatest number of units in any aircraft power service are the actuators, and these form the largest engineering bulk, representing about 50% of the complete system weight.

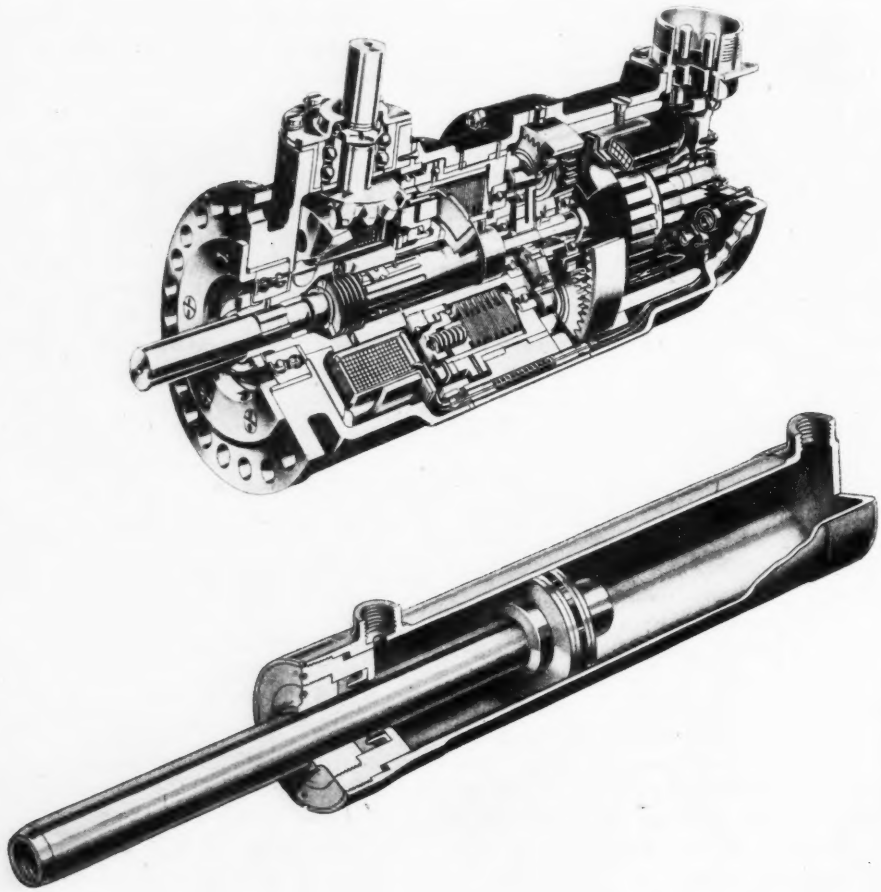


Fig. 1
Sections through Electric and Hydraulic Actuators.

When considering such factors as weight, cost and maintenance, it is not inappropriate that we should first compare the construction of the respective types of actuators.

Sections through hydraulic and electrical actuators are shown in Fig. 1. It is apparent that the simplicity of the hydraulic jack is such that it can be produced for a fraction of the cost of the electrical unit with its motor, clutch, brake, limit switches, gear box, worm shaft, etc. It is also apparent that the hydraulic jack is infinitely simpler to maintain; hydraulic systems being free from the troubles of electrical equipment in damp climates.

It has been suggested that landing gear should be self lowering under gravity. Other than for sideways retractions, it is not considered that gravity lowering is satisfactory, especially for civil air-liners where it is imperative that the undercarriage must be lowered and securely locked before landing. With hydraulic actuation, it is simple to provide an emergency system by the use of compressed air or a slow burning cartridge. Such an emergency system can be provided at the cost of a very few pounds in weight.

I do not believe it is economic to operate every service on an aeroplane by one power source. Certain services can be better operated electrically, others hydraulically, and others pneumatically. If we are to obtain the simplest, lightest, and best aeroplane, we must be prepared to mix the systems judicially and so obtain optimum results. For linear motion where heavy loads must be handled and where emergency actuation is necessary, hydraulic operation provides by far the simplest system.

Installation Layouts.

The fundamental aircraft hydraulic system is well known and no description is necessary.

In fighter aircraft one engine driven pump usually operates all power services, whereas two pumps are normally employed on bomber hydraulic services.

It is interesting to examine the alternative layouts of such installations. Fig. 2 shows twin pumps (usually driven from the inboard engines) delivering to a common system. This arrangement offers the advantage that failure of one pump or one engine does not prevent operation of the hydraulic system.

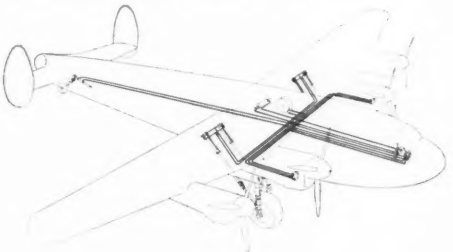


Fig. 2
Twin Pump Hydraulic Installation
(Common System)

Manually operated control valves are positioned in the cockpit or engineer's compartment. Alternatively these valves may be grouped aft and operated by mechanical remote controls.

Fig. 3 illustrates a twin pump installation in which each pump operates the undercarriage on one side of the aircraft. One of these pumps also provides the power source for the retracting tail wheel and the other actuates the landing flaps. This arrangement utilises the minimum length of piping and shows to advantage where remotely controlled electro-hydraulic valves are employed.

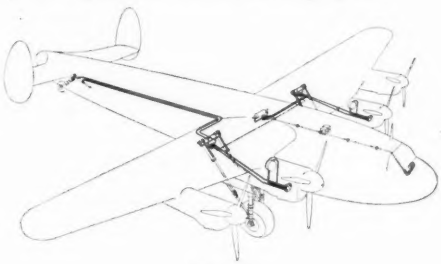


Fig. 3
Twin Pump Hydraulic Installations
(Separate Systems)

A further arrangement shown in Fig. 4 incorporates a separate power unit for each service, comprising an electrically driven pump, reservoir, and pressure switch. With reversible motors and pumps, control valves are

unnecessary. The reservoir is of small capacity, sufficient to cater for a volume slightly in excess of the piston rods. The pump is submerged in the reservoir and the only piping required is short lengths from the power unit to the jacks. The pump is only running while the service is operating.

Fig. 4
Hydraulic Installation with Individual Power Units.

At the limit of actuator travel the pressure rises and operates a switch to stop the electric motor. An illustration of such a power unit is shown in Fig. 5. With this arrangement, installation time and vulnerability are reduced to a minimum.

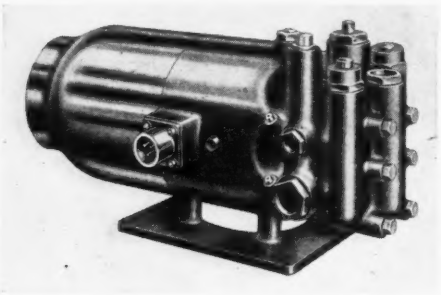


Fig. 5
Electro-Hydraulic Power Unit.

In comparing hydraulic versus electric actuation, consideration must be given to electro-hydraulic systems. Electric control of hydraulic services takes advantage of both systems. Hydraulic power is the simplest means for obtaining linear travel and the standard aircraft low voltage electric system can be used for valve operation through the medium of solenoids.

In such arrangements, hydraulic units can be closely grouped, obviating the disadvantage of servicing a dispersed collection of components.

The reduction in length and number of pipes following such grouping is considerable. Control valves are situated near the actuators and pipe lines in the cockpit are eliminated. In addition to weight saving, such an arrangement improves efficiency by giving a lower pressure drop, due to the shorter pipe lines and reduced number of bends. A typical electro-hydraulic test rig is shown in Fig. 6.

Hydraulic power is generated by two pumps driven by electric motors. Electro-hydraulic units are mounted on the centre panel below which are button controls. In practice the solenoid valves are located close to the jacks.

Figs. 7 and 8 illustrate the weight saving of electrically controlled high pressure systems over low pressure installations with manually operated valves.

American practice is dealing with hydraulic installation differs from British. In this country responsibility for a complete installation is usually left to a specialist firm, whereas in America it is common practice for each aircraft company to produce its hydraulic installation utilising components provided by a number of different firms.

The British procedure appears logical and more economical. Specialist Companies obtain greater experience than those firms producing an occasional installation and responsibility for satisfactory functioning is not shared among a number of Companies.

The ideal characteristics of power installations are:—

(1) Visible controls easily operated with a gloved hand.
(2) Control operations reduced to a minimum.
(3) Minimum manual effort.
(4) A minimum of equipment located in the cockpit.

There is a tendency to make hydraulic systems partly automatic. How far this may

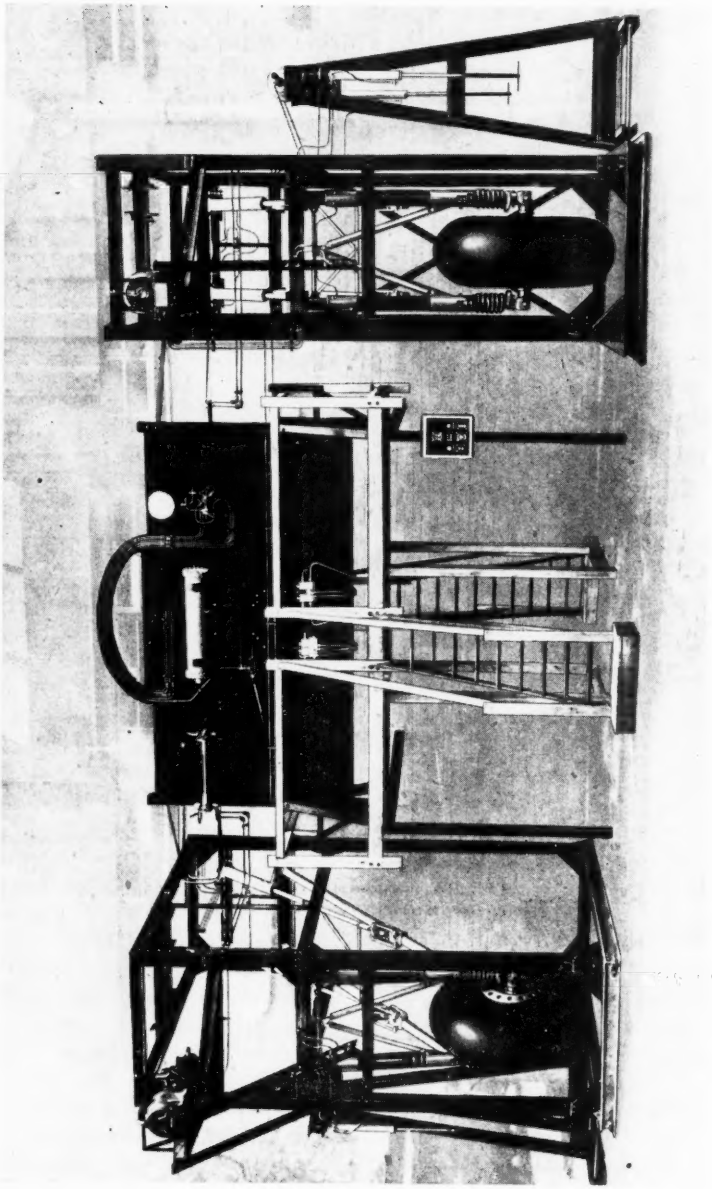


Fig. 6
Hydraulic Test Rig.

COMPARATIVE WEIGHTS OF LOW AND HIGH PRESSURE HYDRAULIC CIRCUITS. FOR AN AEROPLANE OF 70,000 LBS A.U.W.

COMPONENT	LOW PRESSURE CIRCUIT		HIGH PRESSURE CIRCUIT		WEIGHT SAVED
	Nº OFF	WT LBS	Nº OFF	WT LBS	LBS
RESERVOIR & OIL	1	33·50	1	20·00	13·50
ENGINE DRIVEN PUMP	2	22·25	2	18·68	3·57
AUTO CUT-OUT	1	5·62			5·62
ACCUMULATOR & OIL	1	12·94			12·94
HAND PUMP	1	3·62	1	3·56	·06
U/C JACKS & OIL	4	222·24	4	125·00	97·24
FLAP JACK & OIL	1	54·25	1	21·75	32·50
HOT AIR INTAKE JACK	4	1·25	4	1·25	
U/C CONTROL VALVE	1	5·62	2	14·5	− 5·44
FLAP CONTROL VALVE	1	4·62	2	1·18	
FUEL JETTISON VALVE	1	1·87	1	3·68	− 1·81
HOT AIR INTAKE CONTROL VALVE	1	1·68	1	1·00	·68
EMERGENCY AIR VALVE	2	1·25	3	4·87	·62
EMERGENCY AIR NON RETURN VALVE	2	4·24			
E.A.R CONTROL VALVE	1	·70	1	·70	
NON-RETURN VALVE	8	3·74	6	1·00	2·74
THERMAL RELIEF VALVE	2	1·50	2	1·50	
- - -	2	·50	2	·50	
PIPING, CONNECTIONS & OIL		105·00		64·00	41·00
TOTALS		**486 LBS**		**283 LBS**	**203 LBS**

Fig. 7
Comparative Weights Low Pressure and High Pressure Hydraulic Circuits.

eventually go is unknown but automatic controls are at present ahead of requirements.

A system is functioning in which an undercarriage retracts automatically at pre-determined time after take-off.

There is a middle path between extremes. On the one hand the simplest hydraulic system gives the pilot a "drill" to remember and perform, whereas, a high degree of automatic action with safety interlocking can be unduly complicated. (The present policy is to steer between these in favour of the latter. It is presumed that this bias will become more pronounced as the fear of "gadgets" is dispelled by successful service.)

The most important limitations after those set by the pilot, are those demanded by the nature of the aircraft and weight and layout considerations.

An examination of the aircraft manufacturer's needs shows a desire to develop a unit construction plan. Much progress has been

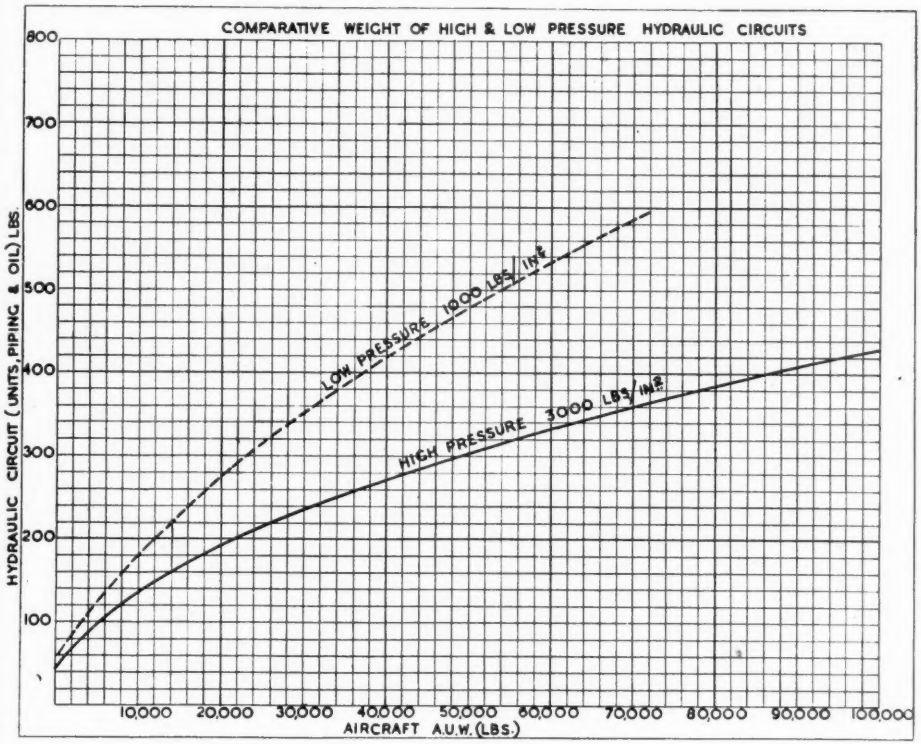


Fig. 8
Comparative Weight of High and Low Pressure Hydraulic Circuits.

made in arranging units for easy installation. Some firms are considering the use of a central "hydraulics panel" which can be inserted as a unit.

Hydraulic equipment must be simple, robust, of low weight and easy to maintain. The three most usual tasks are:—

(1) Filter cleaning;
(2) Topping-up reservoir;
(3) System bleeding.

Where filters are fitted external to the reservoir, these should be of the self-sealing type in which the pot containing the element can be readily removed and replaced without loss of oil.

Bleeding is a process which has been reduced to a simple routine.

The design of hydraulic components requires careful study to ensure neat piping runs. As a general rule piping connections should be confined to one or two sides of a component (assuming these to be of a general cube shape), as this permits latitude in mounting the unit.

Other limitations upon design are due to the nature of the duty required.

First in importance is temperature. A wide range of temperature can be traversed in a short time. These have been quoted as $+150°$ F. to $-65°$ F., but air temperatures as low as $-85°$ F. have been recorded. The resulting changes in volume have a marked effect on a closed circuit containing oil, but excessive pressures can be prevented by thermal relief valves.

Fluid viscosity is affected by temperature. Oil companies have been active in solving this problem and have provided fluids which have

a low rate of viscosity change with temperature (*i.e.*, a "high viscosity index").

Cavitation due to reduction in barometric pressure affects pump efficiency giving rise to reduced and erratic delivery with considerable noise and vibration. There are two means of dealing with this problem: (1) a closed or pressurised system having capacity to absorb the maximum displacement and strong enough to maintain ground level internal pressure when outside pressure falls with altitude; or (2) a reservoir with submerged pump.

Aircraft Hydraulic Pumps.

Studies made by aircraft manufacturers in this country and the U.S.A. indicate that best economies are attained by operating pressures of approximately 3,000 lb. per square inch. British and American pumps operating at these pressures are now available. The maximum pressure of gear pumps is 1,500 lb. per square inch. Above this pressure the stall leakage makes their use prohibitive. The gear pump is therefore unsuitable for future power systems.

The ideal pump must be highly efficient, compact and light. Delivery must be free from pulsations and the pump capable of operating at high r.p.m. without excessive heating. It must operate effectively through temperatures ranging from $+150°$ F. to $-65°$ F., and under atmospheric conditions ranging from sea level to 40,000 ft. without cavitation or air inclusion.

Apart from operating landing gear and

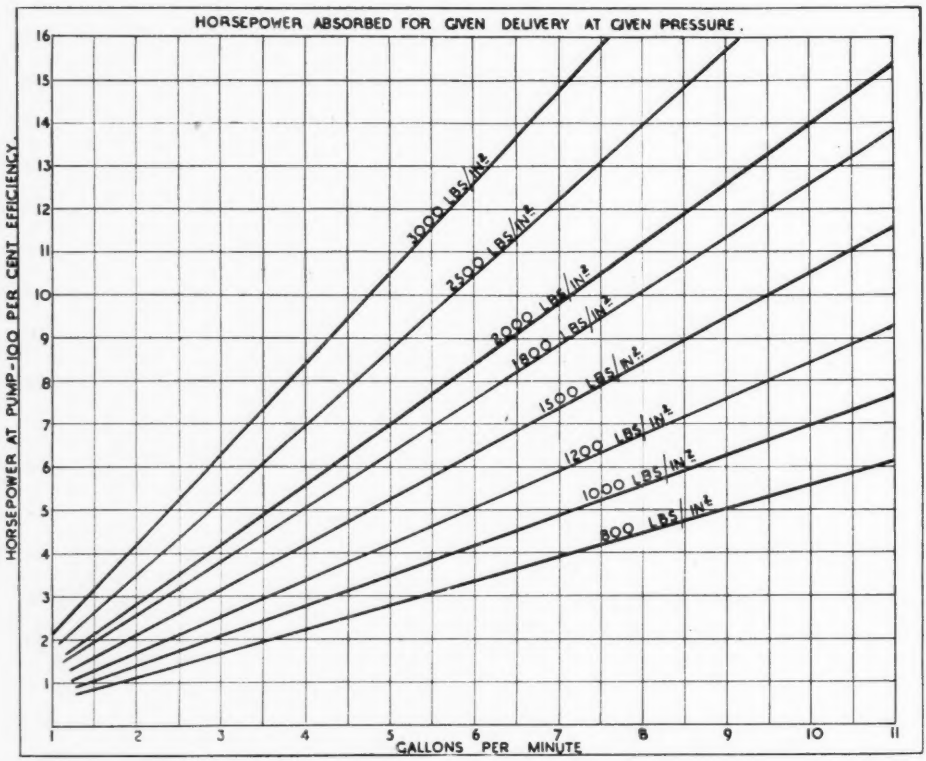


Fig. 9
Graph of Fluid Horse-power.

wing flaps the power required is small. The size of the pumps is usually determined by the landing gear actuating units. Fig. 9 shows a graph of fluid horsepower corresponding to various deliveries and pressures.

Pumps can be divided into four general classifications, and each of these classifications can be sub-divided.

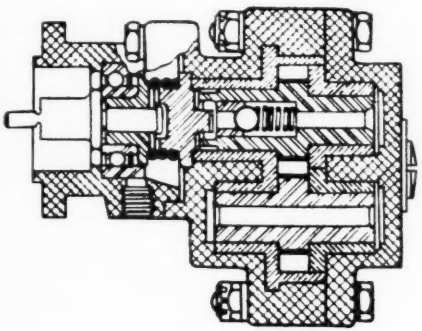


Fig. 10
Pesco Gear Pump.

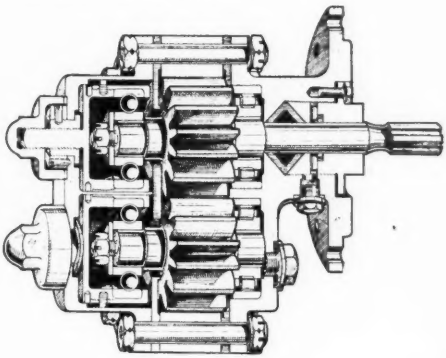


Fig. 11
Dowty Gear Pump

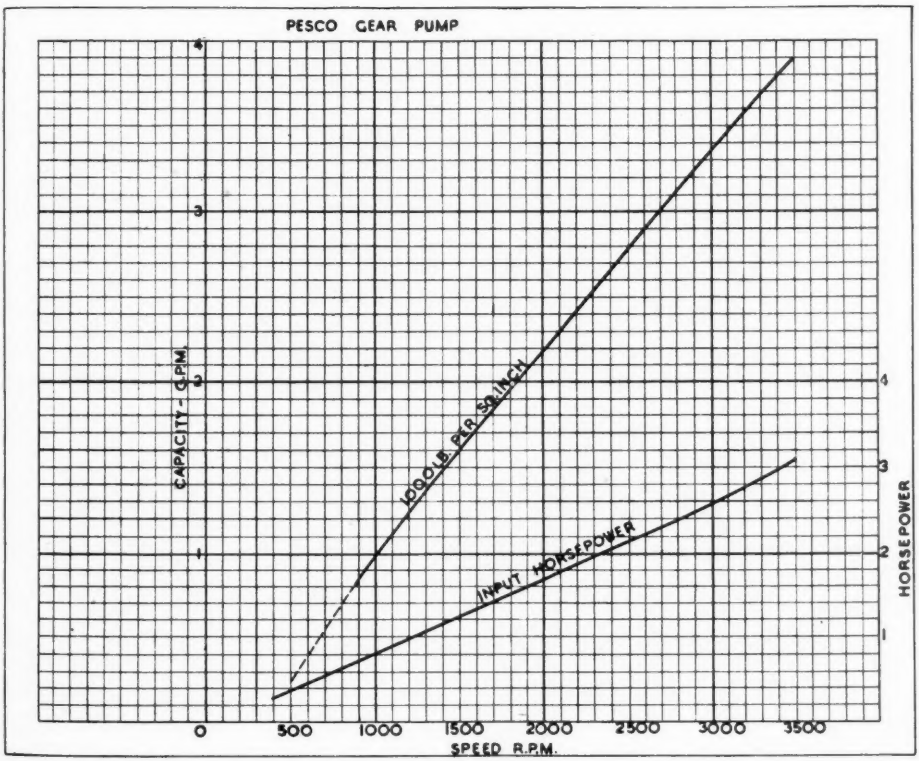


Fig. 12
Pesco Gear Pump—Performance Curves.

Types of Hydraulic Pumps.

(1) Rotary Pumps (Constant Delivery):
  a. Gear Pumps.
    (1) Driver and driven Gear Wheels.
    (2) Gerotor.
  b. Vane Pumps.
    (1) Eccentric Rotor.
    (2) Cam Riser.

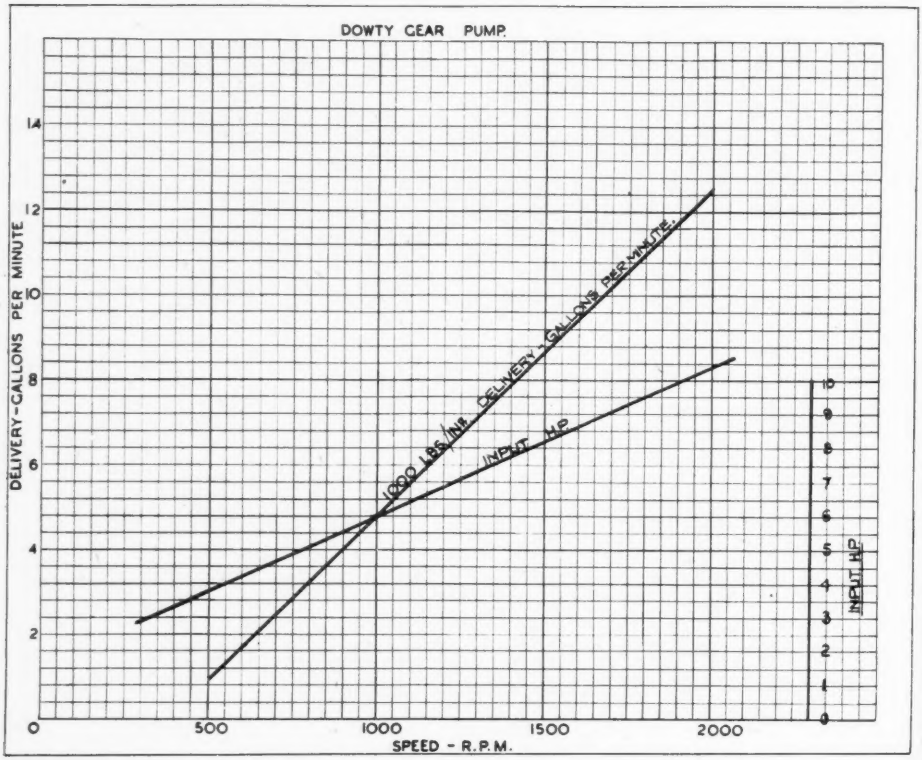


Fig. 13
Dowty Gear Pump—Performance Curves.

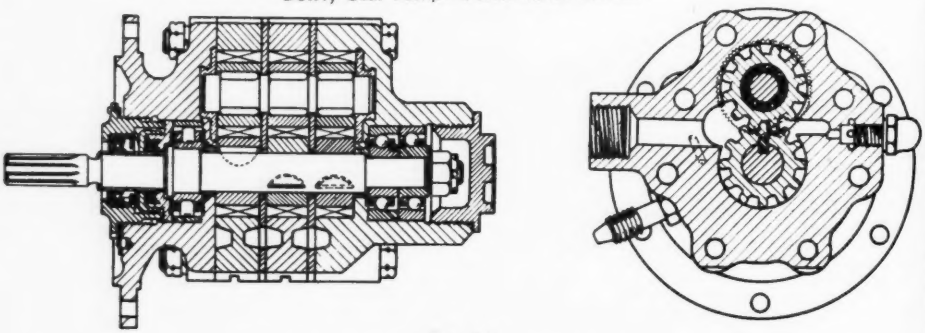
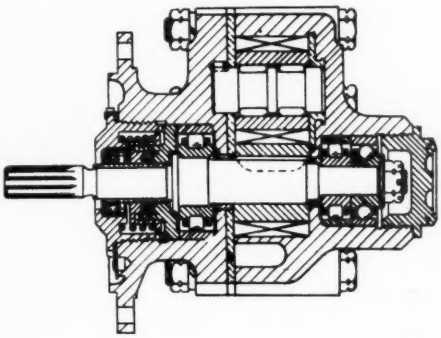


Fig. 14
Integral Gear Pump, Type B.H. Mk. IV.

(2) Reciprocating Pumps:

a. Angular Piston Block.

(1) Constant Delivery.



(2) Variable Delivery.

b. Radial Piston Pump.

(1) Constant Delivery.

(2) Variable Delivery.

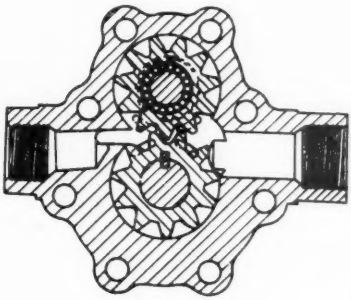


Fig. 15
Integral Gear Pump, Type I.H.C. Mk. II.

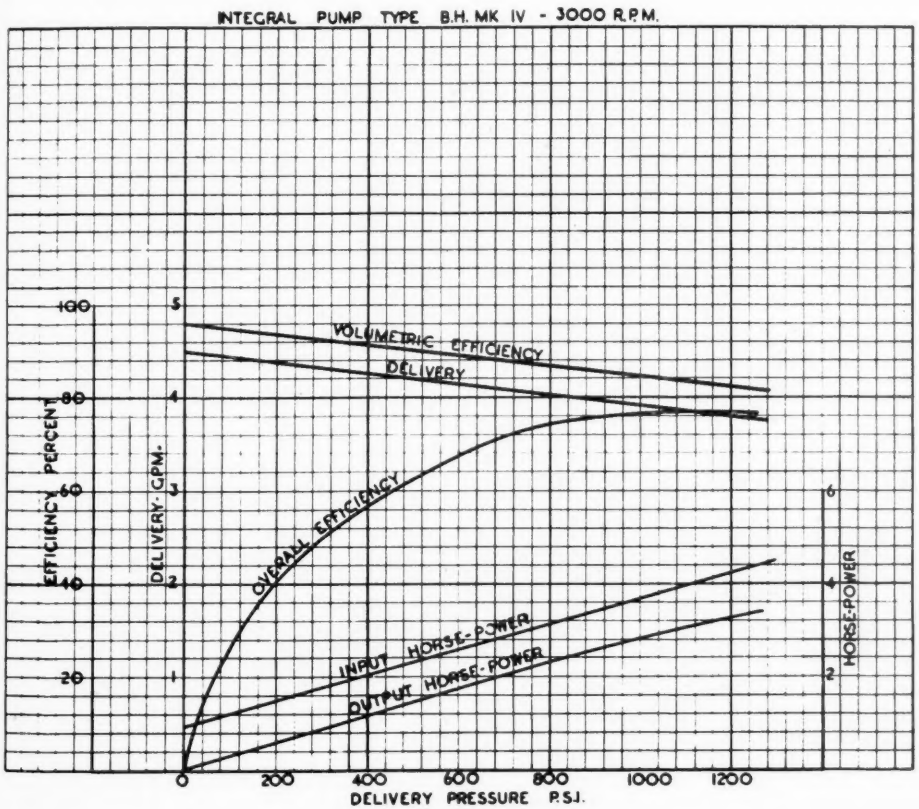


Fig. 16
Integral Pump, Type B.H. Mk. IV—Performance Curves.

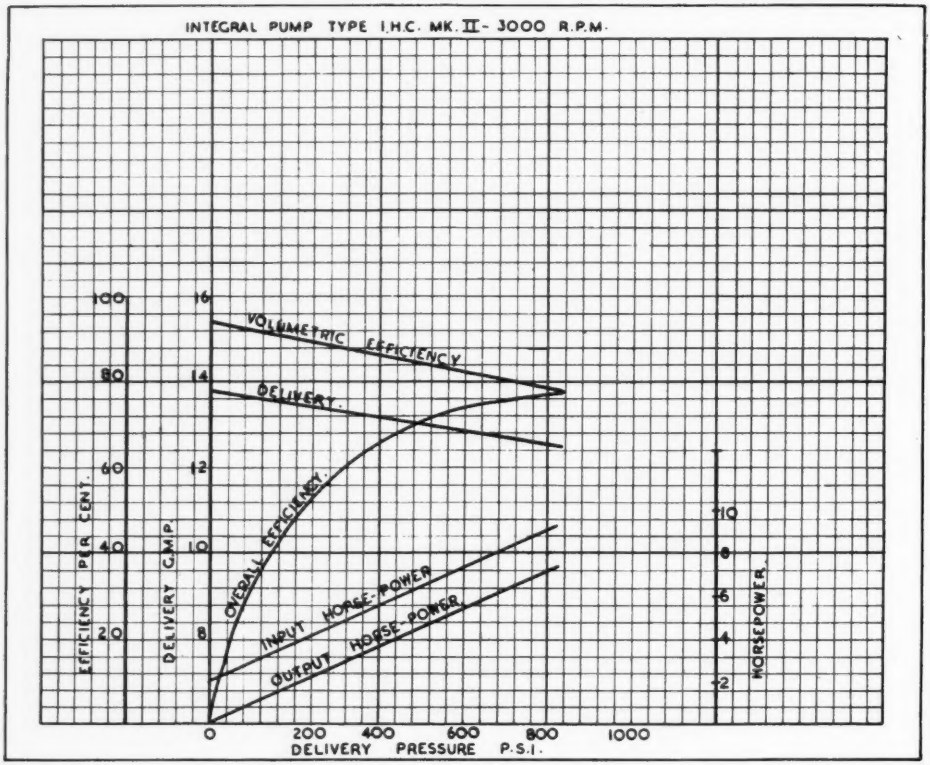


Fig. 17
Integral Pump, Type I.H.C. Mk. II—Performance Curves.

c. Swash Plate.
  (1) Constant Delivery.
  (2) Variable Delivery.

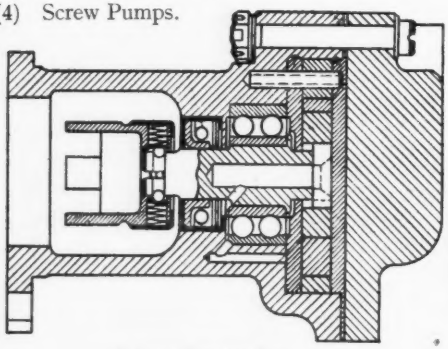
(3) Centrifugal Pumps.

(4) Screw Pumps.

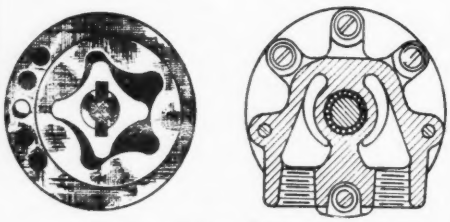
Rotary Pumps.

The gear pump has been the most widely used. The clearances between the gears and casing are closely held to obtain high efficiency. The fluid flow is smooth and the rate dependent only on rotational speed.

A gear pump produced by Pesco is shown in Fig. 10. A similar unit manufactured by



Eclipse Gerotor Pump.



Porting—Eclipse Gerotor Pump.

Fig. 18

Dowty Equipment is shown in Fig. 11. Performance of these pumps are given in Figs. 12 and 13 respectively.

Integral Auxiliary Equipment Pumps are of the gear type, and are available in the single, duplex, and triple-stage form. With

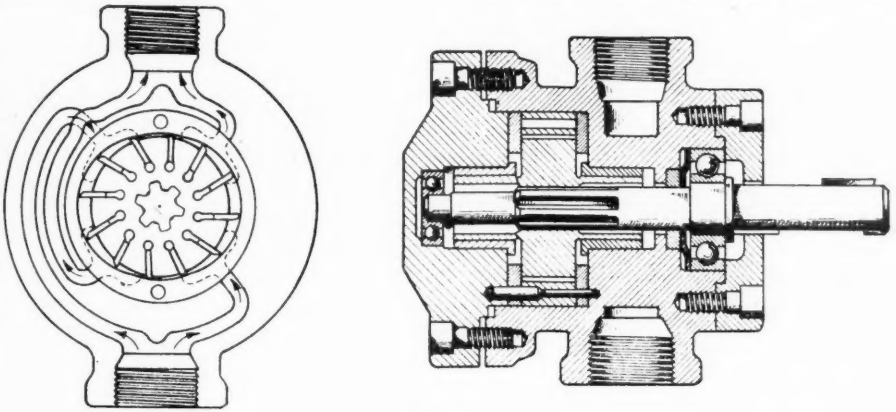


Fig. 19
Vickers (U.S.A.) Vane Pump.

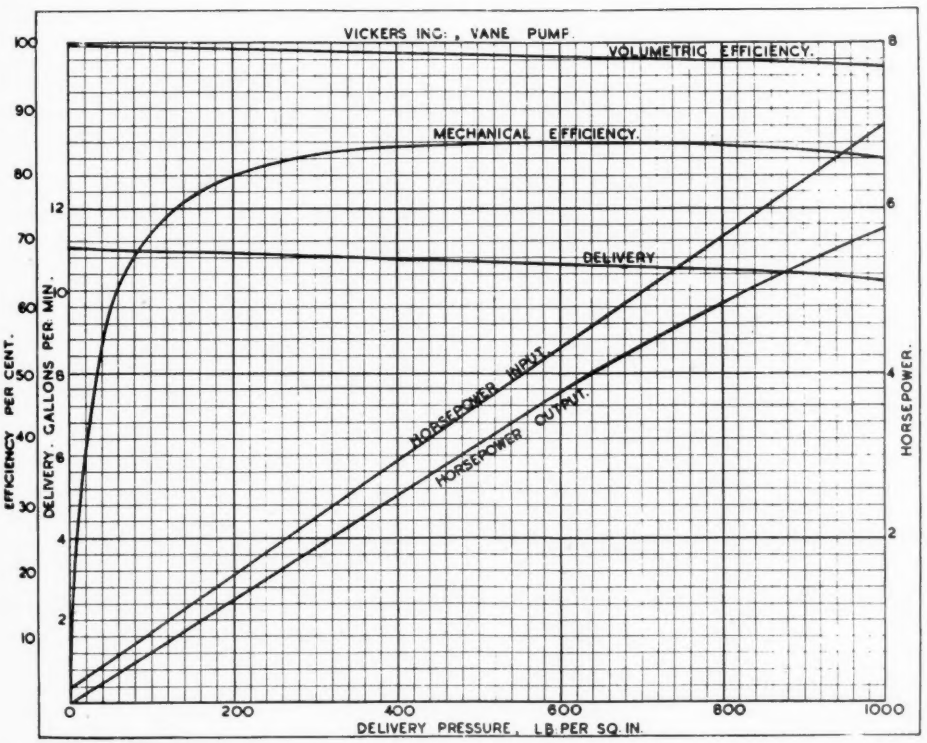


Fig. 20
Vickers Inc. Vane Pump—Performance Curve

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multi-stage pumps fluid is led successively through each set of gears. Illustrations of two typical I.A.E. pumps are given in Figs. 14 and 15, with performance curves in Figs. 16 and 17.

The duplex pump incorporates one set of large gears and two sets of smaller gears. By this means, a low pressure, high delivery is made at the first stage, and a high pressure low delivery at the second.

Duplex Pump 1 *B.H. Mk.* 1.	*Single Stage*	*Two Stage*
Normal Working Pressure	300 lb./sq. in.	600 lb./sq. in.
Delivery	8.1 gals./min.	4.0 gals./min.
Normal Speed	2,250 r.p.m.	
Power Absorbed	5.7. h.p.	
Maximum Pressure	300 lb./sq. in.	600 lb./sq. in.
Weight	9.5 lb.	

The Gerotor pump shown in Fig. 18 is produced by the Eclipse Division of the Bendix Aviation Corporation. This pump operates at 1,000 lb. per sq. inch at 2,500 r.p.m.

The Gerotor pump has an internal gear, driven by a spur gear having one tooth less than the internal gear.

The Vane type pump has not found many aircraft applications due to its inherent defects under high pressure.

Fig. 19 illustrates a Vickers (U.S.A.) Vane pump. This pump embodies a slotted rotor carrying a number of flat steel blades. The rotor is concentric with the pump shaft, and the blades are thrown against an elliptical face by centrifugal force.

As the rotor revolves fluid is drawn in between the blades from the suction ports into the larger volume section of the casing, then carried around to the discharge ports. Performance figures are shown in Fig. 20.

Piston Pumps.

Reciprocating piston pumps are the only ones achieving high pressures with high efficiency. As each cylinder generally contains an inlet and outlet valve, these valves are necessarily small, thus complicating the design and making the elimination of cavitation difficult. Some designs avoid valving each cylinder by allowing the cylinder block to rotate on a fixed shaft, with inlet and outlet ports.

The radial type pump lends itself well to multiple piston arrangements. The increased number of pistons and the short stroke practically eliminate pulsations.

Many such types of pump have been produced. Noteworthy are the V.S.G., Lockheed and Dowty Live Line.

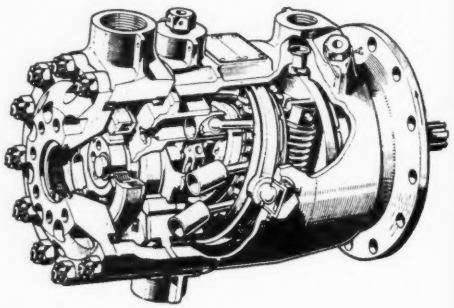


Fig. 21
V.S.G. Pump.

The V.S.G. pump shown in Fig. 21 is of the variable delivery swashplate type. Pressure is continuously maintained in the delivery line. When flow is not required the outlet is closed and delivery ceases.

A general arrangement of the Lockheed Mk. VI fixed delivery pump is given in Fig. 22, and performance figures in Fig. 23.

Each cylinder wall has three inlet ports communicating with the interior of the casing and with the suction connection in the cover. The cylinders are disposed radially about the

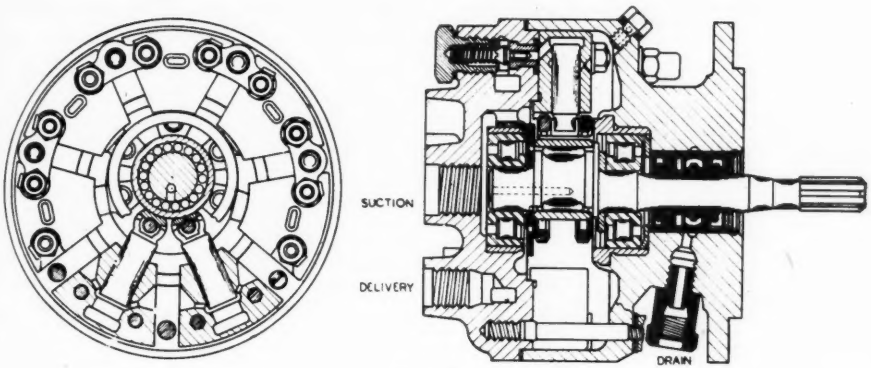


Fig. 22
Lockheed Mk. VI Pump.

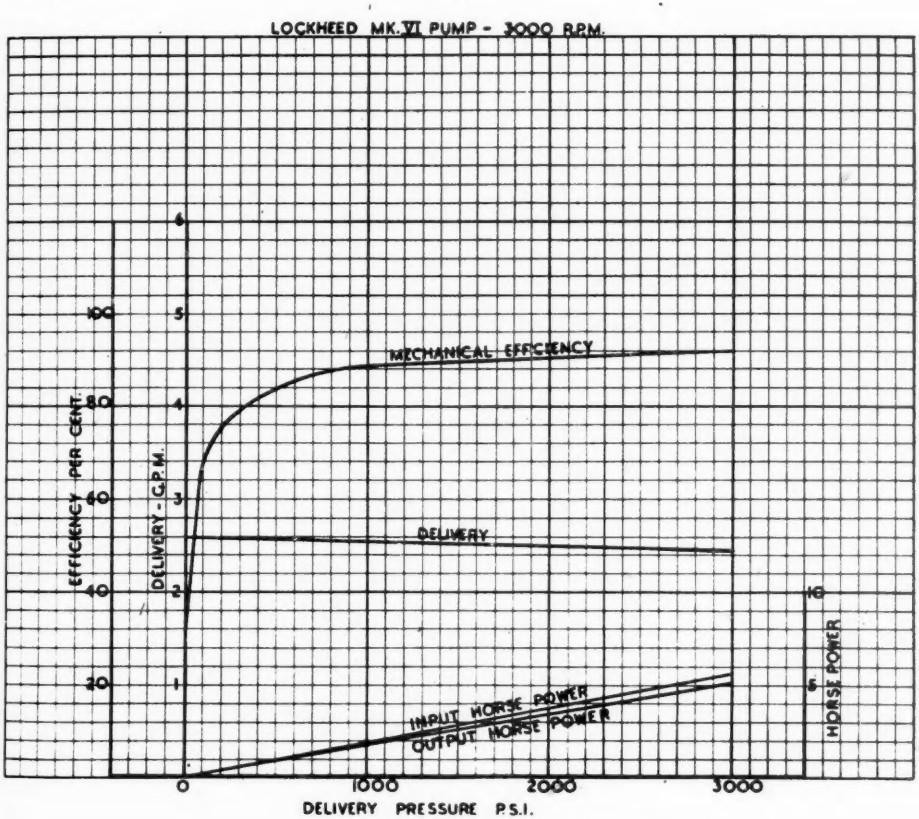


Fig. 23
Lockheed Mk. VI Pump—Performance Curves

drive shaft which has an eccentric in way of the pistons. A shoe on each plunger bears on a ring carried on the eccentric.

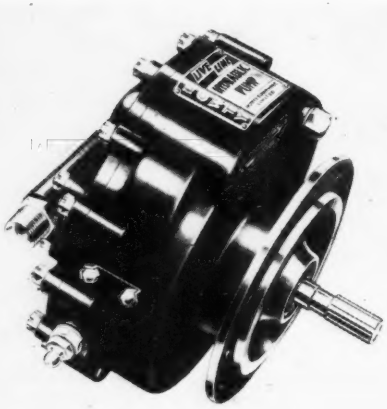


Fig. 24
Dowty Live Line Pump

The inlet porting is automatic, the cylinder walls being pieced so that the apertures are uncovered just before the plungers reach the end of their outward stroke. After moving into the cylinders a short distance, the plungers cover the inlet ports and further movement forces the trapped fluid through delivery valves to the outlet connection.

Dowty Equipment have developed the Live Line radial piston pump based on the original design of Major H. N. Wylie.

Features are incorporated which allow for high pressures and automatic operation. The most important is the automatic cut-off at peak pressures. Pressure is maintained at all times and when any circuit is operated the pump immediately commences to deliver fluid under pressure. The pump is of the variable delivery type and flow is automatically regulated to suit the requirements of each service.

Figs. 24, 25 and 26 show the "Live Line" pump. It has a central fixed shaft with suction and delivery ports for valving fluid to the cylinder block which rotates about it. The cylinder block has seven radial cylinders each containing a piston carrying a pivoted slipper at its outer end. As the cylinder block rotates the pistons are thrown outwards by centrifugal force, the slippers bearing against a circular track ring. This track ring is pivoted

Gear Pumps.	Pressure	Flow		H.P.	H.P.	Weight
Type	lb./sq. in.	Gals/min.	Revs.	Input	Output	lb.
Dowty	1,000	8.5	1,500	8.25	5.95	10.75
Pesco	1,000	3.3	3,000	2.6	2.3	3.5
Integral B.H. Mk. IV	1,200	3.6	3,000	4.25	3.25	7.25
Integral I.H.C. Mk. II	800	12.5	3,000	9.25	7.2	7.2
Vane Pumps.						
Vickers	1,000	8.9		7	5.8	
Piston Pumps.						
Vickers Variable	1,700	12.5	2,700	15	13.75	
Dowty L.L. Type 5700	3,000	3.26	2,800	9.75	7.25	9.5
Dowty L.L. Type 6700	750	8	2,800	6.3	4.2	9.8
Dowty L.L. 700 Type 1068	700	2.8	2,800	1.85	1.37	8
Vickers Constant	3,000	6.7	3,750	15	12.8	6.8
Lockheed Mk. VI	3,000	2.5	3,000	5.7	5.3	7.75
V.S.G. Mks. VB and VI	1,000	3	2,600	3	2.1	
V.S.G. Mks. VII and VIII	1,000	8.3	2,600	7	5.8	

on a knife edge about which it can rock from a position concentric with the fixed shaft to an eccentric position. When it is concentric the pistons have no stroke and when it is in a position of maximum eccentricity they have their maximum stroke. Performance curves are shown in Fig. 27.

A constant delivery axial piston pump by Vickers Inc., Detroit, is shown in Figs. 28

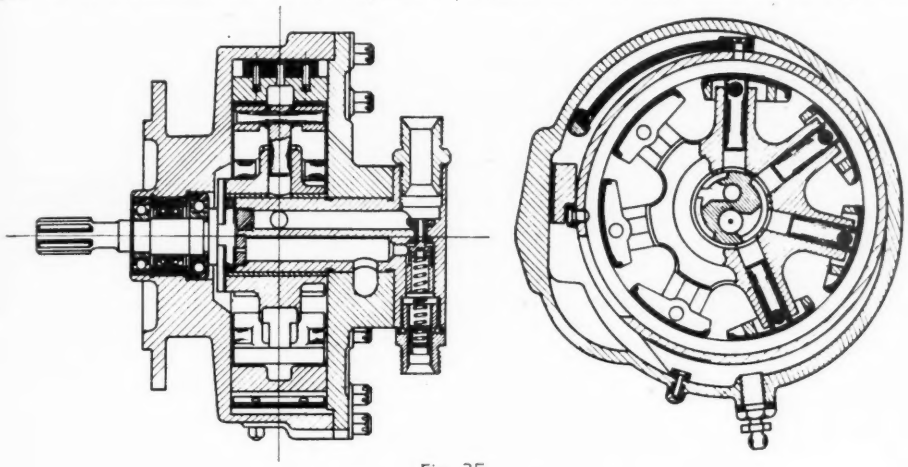


Fig. 25
Dowty Live Line Pump

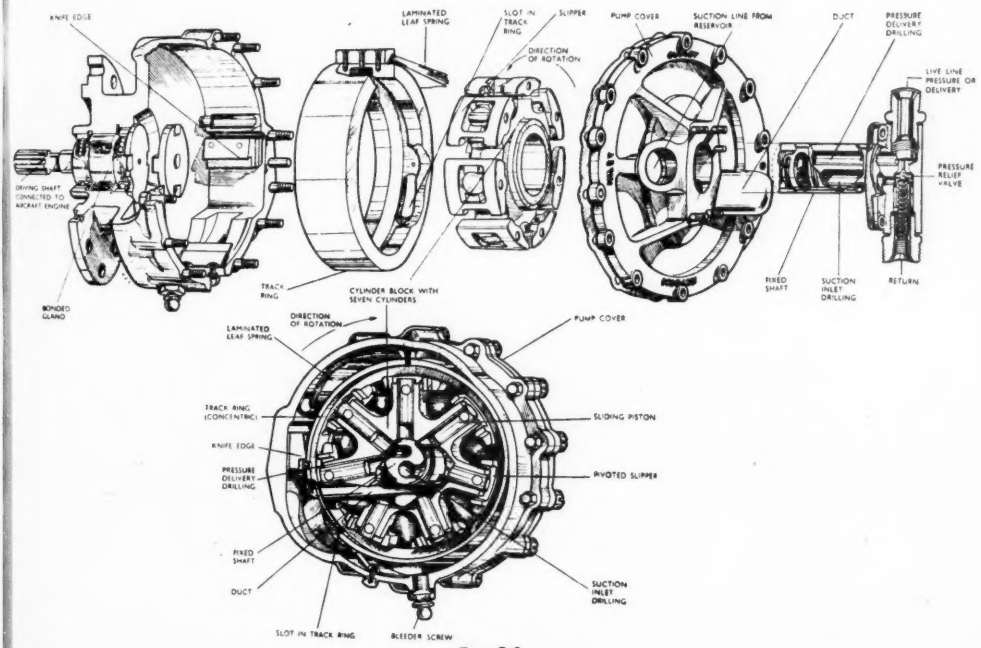


Fig. 26
Dowty Live Line Pump.

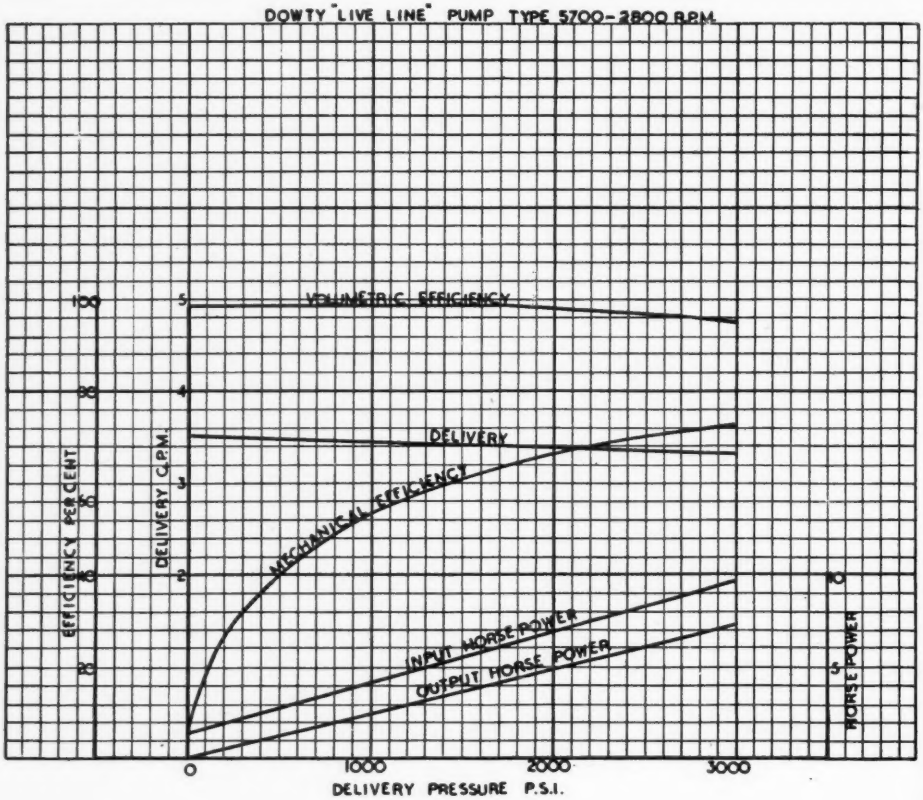


Fig. 27
Dowty Live Line Pump—Performance Curves.

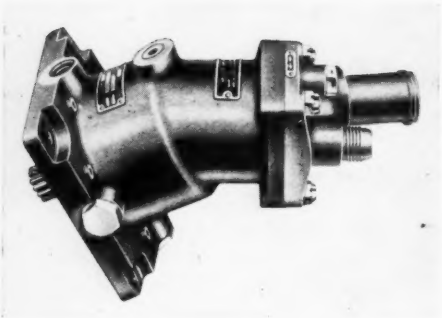


Fig. 28
Vickers Inc. Rotary Axial Pump.

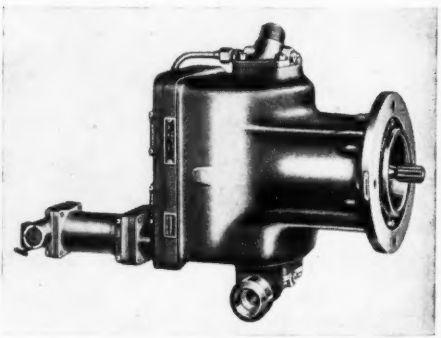


Fig. 31
Vickers Inc. Variable Volume Pump.

(page 388) and 29 (page 391). Performance curves are shown in Fig. 30.

Vickers (Detroit) have also produced a Variable Volume Piston pump with an integral pressure control which automatically maintains the desired pressure independent of varying volume and engine speed.

Fig. 31 illustrates this pump. Performance curves are shown in Fig. 32.

A Pesco Rotary Axial pump is illustrated in Fig. 33. The design, construction and operation are similar to the Vickers unit.

THE EFFECT OF ALTITUDE ON AIRCRAFT HYDRAULIC PUMPS.

Distinguishing features of aircraft hydraulic pumps are their high rotational speed and the high altitude at which they must operate. These conditions introduce problems of starvation in the suction line. Increasing the rotational speed raises the power output without increasing the size and weight of the pump. It appears that a pump which operates satisfactorily at high speed has also good performance at high altitude.

In general, the suction circuit controls pump performance at altitude and also at maximum r.p.m. A critical speed exists for any given suction head beyond which the delivery cannot be increased.

Graphs Figs. 34 and 35 show typical speed delivery curves at various altitudes for gear

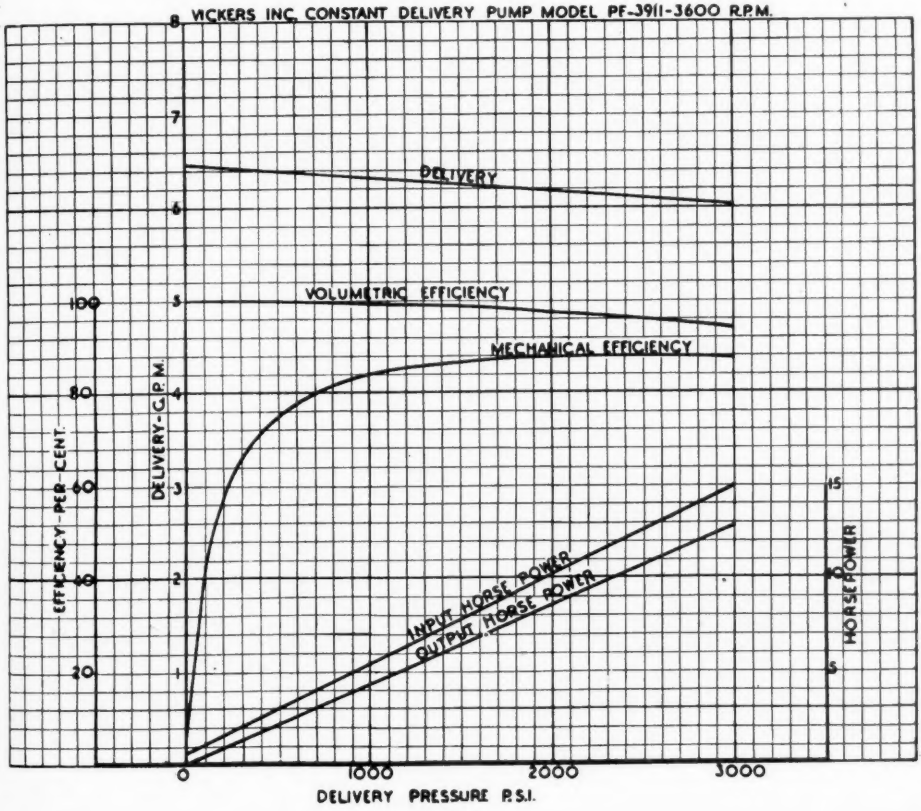


Fig. 30
Vickers Inc. Constant Delivery Pump—Performance Curves.

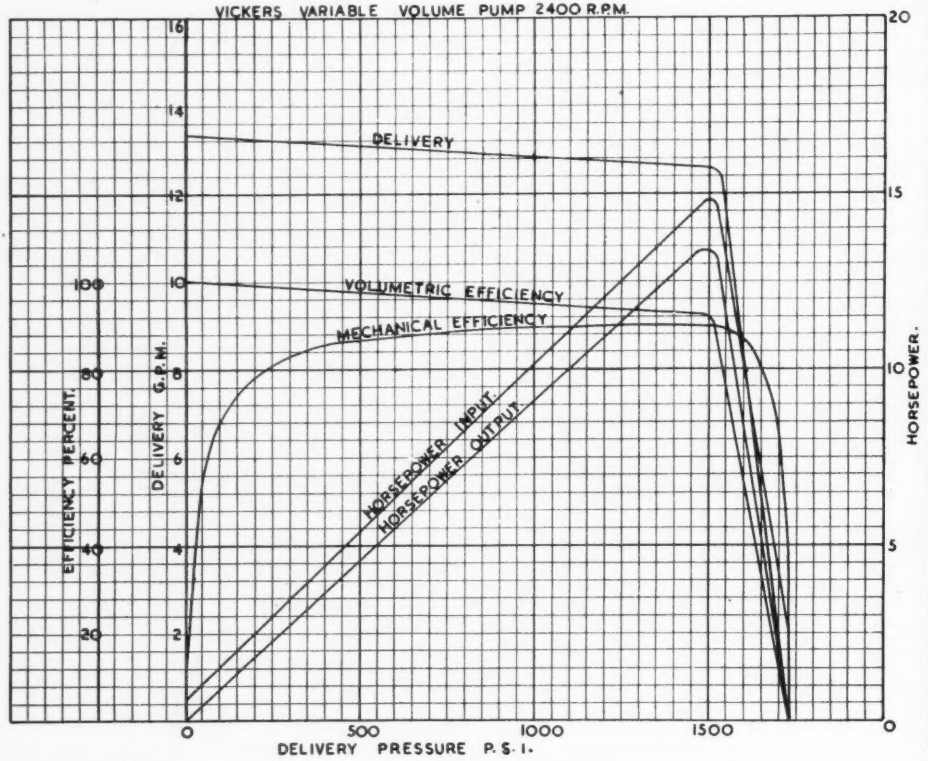


Fig. 32
Vickers Variable Volume Pump—Performance Curves.

and piston pumps. These graphs show the effect of altitude on pump performance and the improvement resulting from pressurising the reservoir.

Considerable improvements can be made at high altitude and high r.p.m. if careful consideration is given to the following design features:—

(1) In general, acceleration of the fluid in the suction circuit is the critical factor. As far as possible, pumps should be primed during suction using the centrifugal force available due to rotary movement.

(2) Sudden changes in direction of flow and any factors tending to increase turbulence in the suction passage should be avoided.

(3) The suction port should be as large as possible.

(4) The suction period should be increased at the expense, if necessary, of the delivery period. In the case of a piston pump where the suction and delivery stroke occupy one revolution, by suitably designing the piston actuating mechanism, a large ratio between the suction and delivery periods can be attained.

Hand Pumps.

With engine driven pump installations it is usual to provide a hand pump for ground operation when the engine is not running and to pressure test pipe lines and joints. It can

also be used in the event of engine pump failure.

Fig. 36 illustrates a double acting pump using only one piston and one pair of valves. The working principle will be understood from the illustration. The oil space is indicated by the black areas. When the piston is raised, oil is drawn in beneath it. On the reverse stroke this oil is expelled through the piston valve into the space above. The cross sectional area of the piston rod is exactly half that of the cylinder, thus half the displaced oil volume is discharged into the delivery pipe. The other half remains above the piston

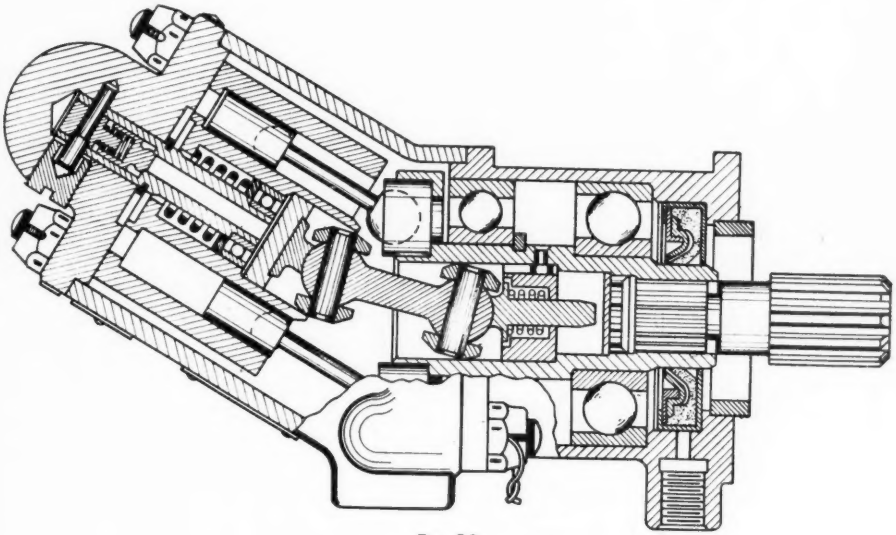


Fig. 29
Vickers Inc. Rotary Axial Pump.

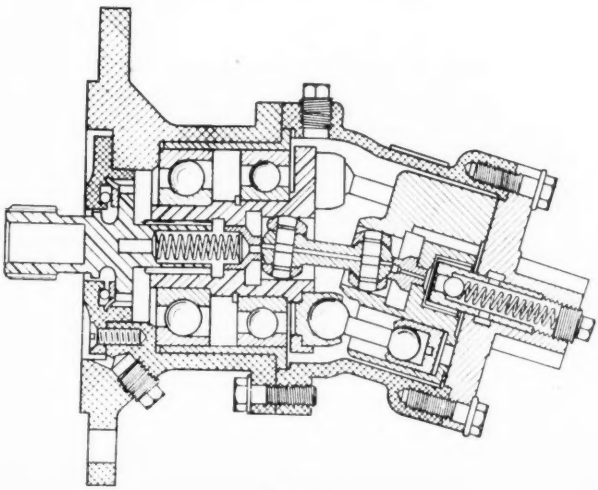


Fig. 33
Pesco Rotary Axial Pump.

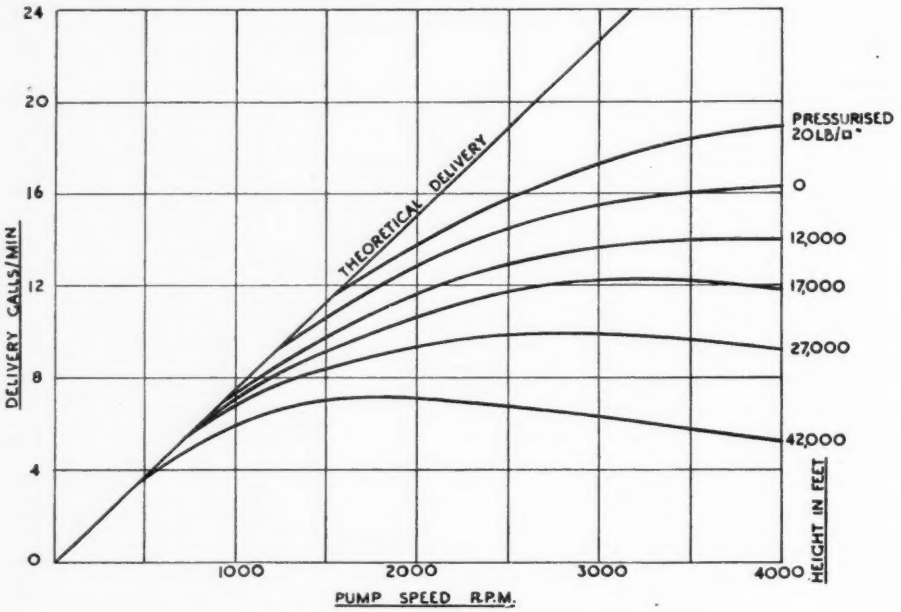


Fig. 34
Speed Delivery Curves at Various Altitudes—Gear Type Pump.

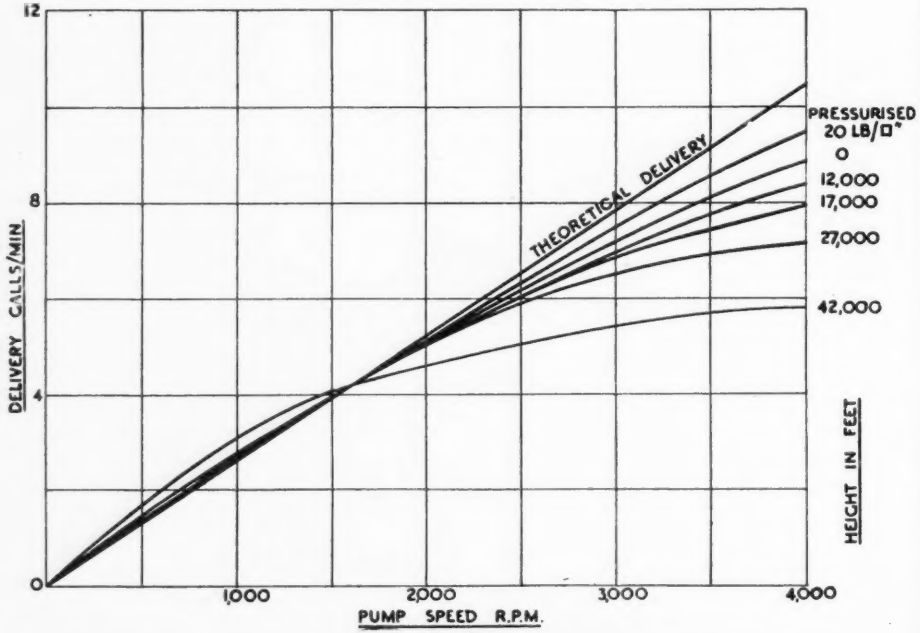


Fig. 35
Speed Delivery Curves at Various Altitudes—Piston Type Pump.

to be delivered on the next stroke, when a further charge is drawn into the cylinder. This type of pump, originally developed by Dowty Equipment, is now used on almost all British and American aeroplanes using hydraulic systems.

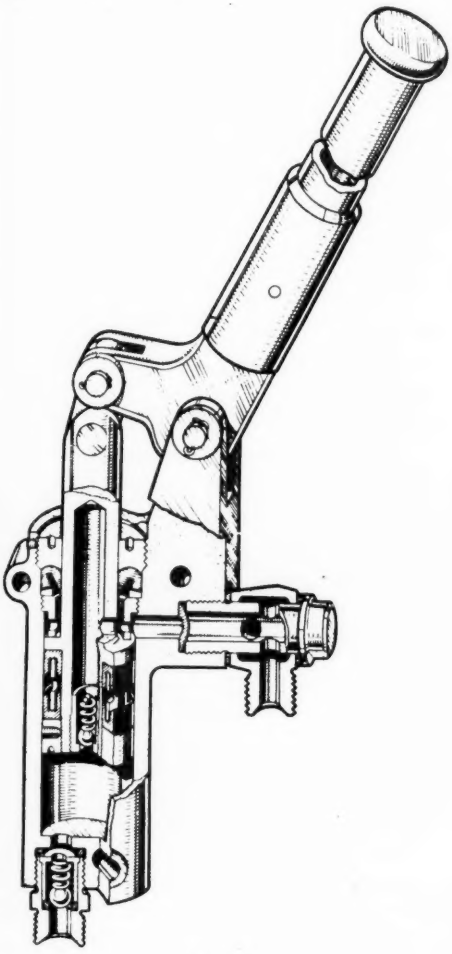


Fig. 36
Dowty Hand Pump.

A variation of this design, Fig. 37, illustrates the hand pump standardised by the Undercarriage Manufacturers' Committee.

The inlet valve is of the poppet type and the rubber piston ring is used as the outlet valve. On the up stroke the piston ring seals a number of drillings in the lower half of the piston and fluid trapped above is forced into the delivery line. On the down stroke the ring uncovers these drillings, allowing fluid to pass to the annular space above the piston.

The Turner duplex hand pump designed to reduce the time and work required in manual operation of hydraulic services is shown in Fig. 38. It comprises two double-acting pumps, one having twice the stroke of the other. When the operating pressure rises to a given figure, the long stroke pump cuts out,

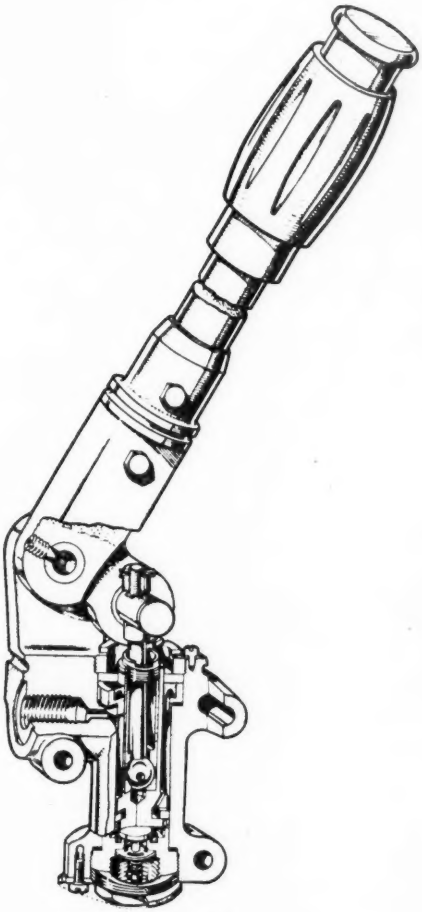


Fig. 37
U.M.C. Hand Pump

allowing the operator to pump at a higher pressure with reduced delivery.

This design is based on the theory that in most hydraulic installations the greater part of the work takes place at low pressure, and the maximum pressure is only required occasionally.

	Pressure lb./sq. in.	Handle Load at 14" R.	Capacity c.c. per double stroke	Weight lb.
Turner Duplex	550-1,500, 2,400	30-30-48	22-7.5-7.5	4.25
Dowty	1,200-1,800	56-84	17	3.6
U.M.C.	1,800-2,500	56-78	10.5	2
Lockheed low pressure	750-1,000	33-45	12.5	4.25
Lockheed high pressure	1,000-2,000-3,000	24-46-64	6.6	2
Messier	2,500	75	13	1.9

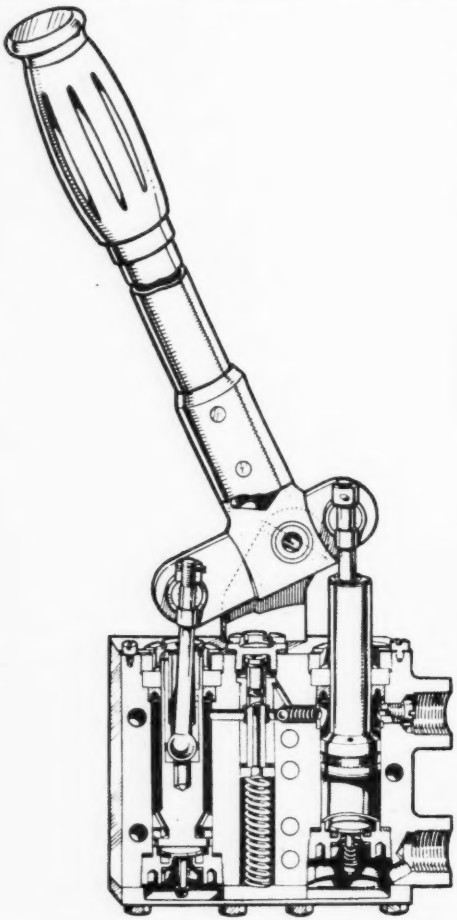


Fig. 38
Turner Duplex Hand Pump.

HYDRAULIC VALVES.

Valves can be grouped and sub-divided as follows:—

1. *Selector Valves.*
   (*a*) Manual;

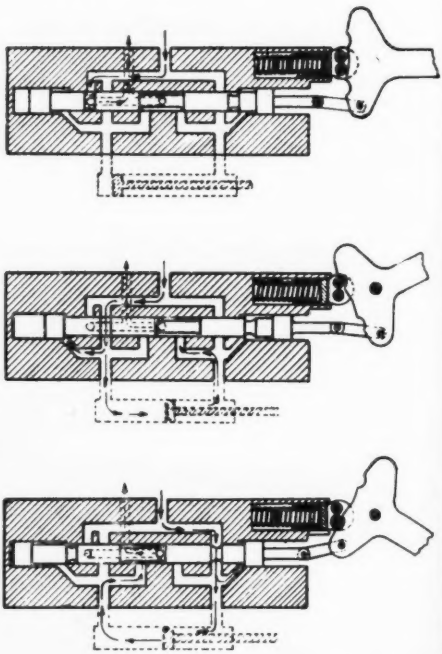


Fig. 39
Diagram of Lockheed Control Valve.

(*b*) Solenoid;
(*c*) Emergency;
(*d*) Pre-selector.

2. *Pressure Valves.*
   (*a*) Relief;
   (*b*) Regulator.
3. *Cut-Out or Unloading Valves.*
   (*a*) Manual;
   (*b*) Automatic.
4. *Locking Valves.*
5. *Restrictor Valves.*
6. *Non-Return Valves.*
7. *Flow Valves.*

It is impossible to cover all types of valves in this paper, but a number of representative types are described.

SELECTOR VALVES.

Selector valves are of three distinct types:—
(1) Sliding plunger;
(2) Rotary disc or barrel;
(3) Poppet.

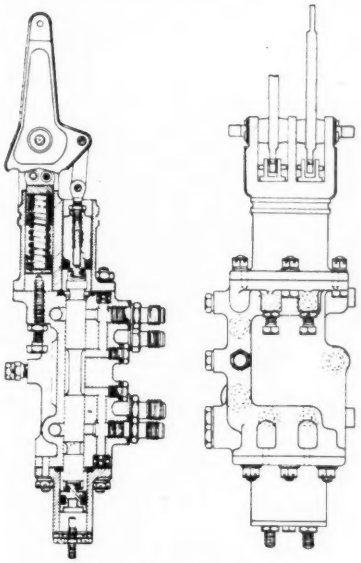


Fig. 40
Lockheed Selector Valve.

Plunger Valves.

Lockheed and Vickers plunger valves are in general use. Fig. 39 shows the settings of the Lockheed valve for extension and retraction of a jack and the neutral positions to which the valve automatically returns after completion of an operation.

In the neutral position both ends of the jack and the pump supply are connected to the reservoir.

Fig. 40 shows a typical Lockheed selector for controlling two services. Units are also produced for controlling one or three services.

The Vickers unit controls an undercarriage circuit, and incorporates switches for the undercarriage position indicator and operates the undercarriage locks. The control unit automatically returns to an idling condition when the undercarriage is fully "up" or "down."

The principle of operation is illustrated diagrammatically in Fig. 41 which shows the cycle of operations when undercarriage "up" is selected. Operation of the indicator switches and mechanism for releasing the undercarriage locks are not shown but one jack is represented in chain line.

The sequence of operations is similar to the Lockheed valve.

Fig. 42 illustrates a typical Vickers control unit.

Rotary Disc or Barrel Valves.

Dowty, Bristol and Vickers have many rotary control valves in general use. Bristol use the ported barrel type, whereas Dowty and Vickers employ disc valves.

The Bristol unit comprises one or more valves in a housing. Fig. 43 illustrates a triple valve controlling the undercarriage and flaps. The third valve acts as a power on-off valve enabling the pump delivery to be by-passed to reservoir.

Fig. 44 illustrates a rotary type valve produced by Dowty and Fig. 45 shows a Vickers type. The principle of both designs is similar.

A rotary control valve, similar to the types previously described, has been produced by the Turner Manufacturing Co. This has com-

pensating springs, so that the operating load is small over a wide pressure range. See Fig. 46.

Poppet Valves.

Dowtys and Messiers have poppet valves which have been extensively used.

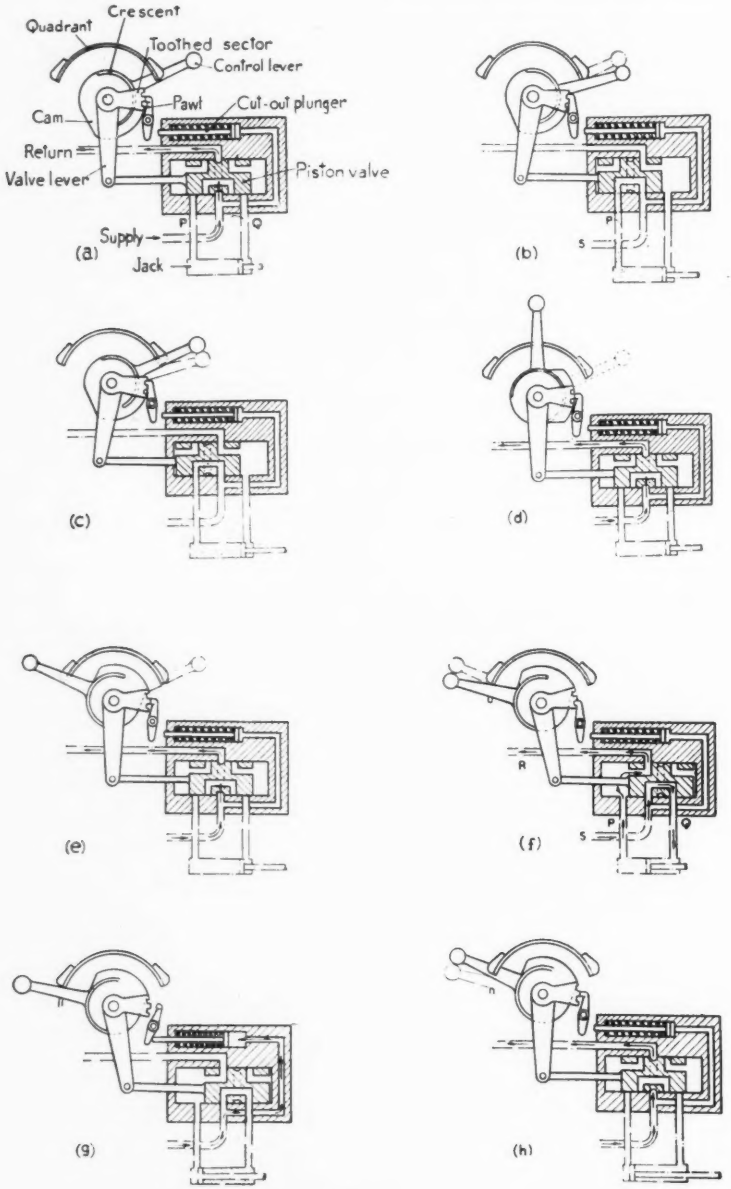


Fig. 41
Diagram of Vickers Control Unit.

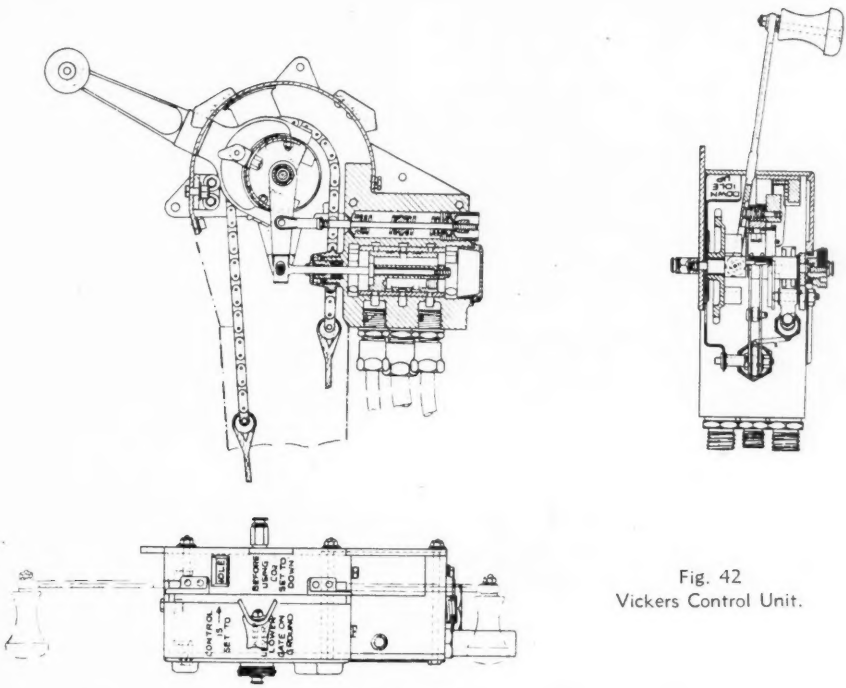


Fig. 42
Vickers Control Unit.

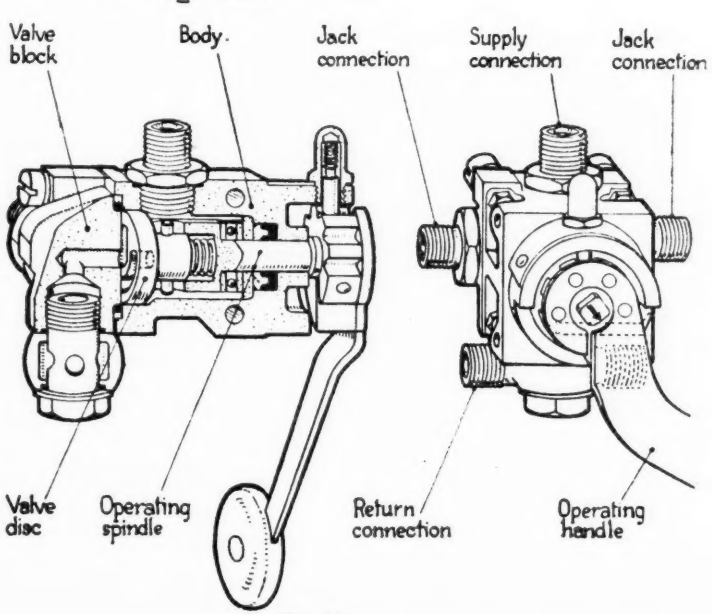


Fig. 44
Dowty Rotary Disc Valve.

Fig. 47 shows a Dowty cam operated valve comprising a body carrying a multi-cam shaft operating spring loaded poppet valve. The valves have synthetic rubber inserts and sit on faces machined in the body. Rotation of the cam shaft lifts the selected valves from their seats and when the lever is returned to neutral the valve re-seat and provide positive hydraulic locks.

The valve illustrated in Fig. 48 is a Messier quadruple distributor type. The control levers normally remain in neutral and are manually held in the "open" or "shut" position during jack operation. These units are used to control any number of circuits.

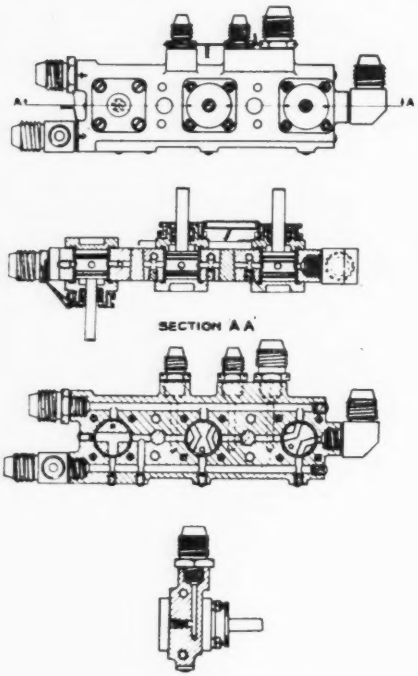


Fig. 43
Bristol Rotary Control Valve.

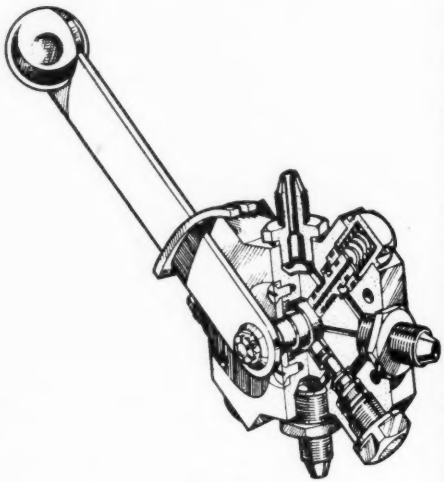
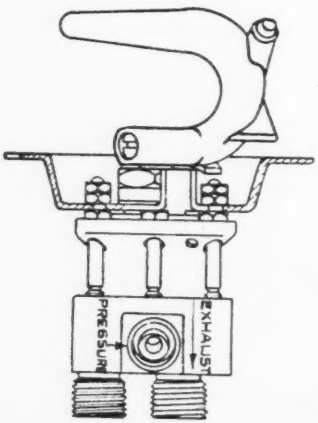


Fig. 46
Turner Rotary Control Valve.



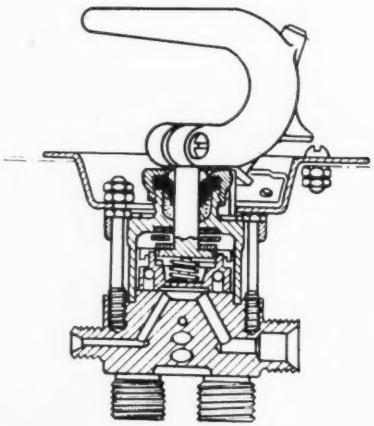


Fig. 45
Vickers Rotary Disc Valve.

The lever base is cam shaped and the lever remains vertical in the neutral position. Movement of the lever to one side or the other allows the cam to lift the poppet valve from its seat. When the lever is released the valves re-seat, and provide a positive hydraulic lock.

Solenoid Valves.

Another type of poppet valve is illustrated in Fig. 49. This is a two-way solenoid valve, produced by Dowty Equipment.

Push-button operation energises the solenoid which lifts the needle pilot valve and allows pressure oil to act on the piston, thus

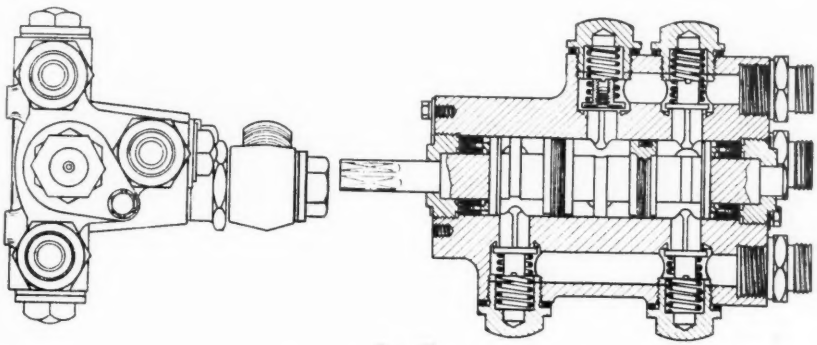


Fig. 47
Dowty Cam-operated Valve.

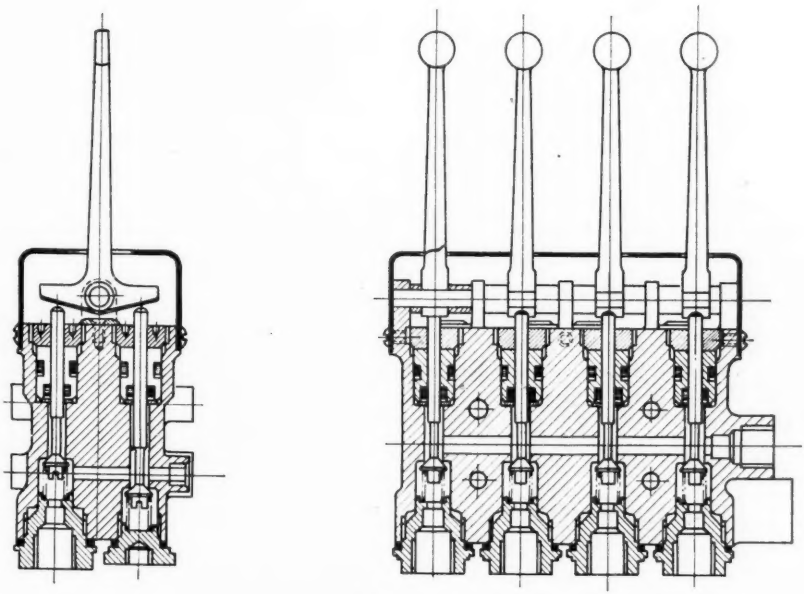


Fig. 48
Messier Quadruple Distributor Valve.

opening the main valve. The control valve is symmetrically arranged and another solenoid is energised for the reverse action.

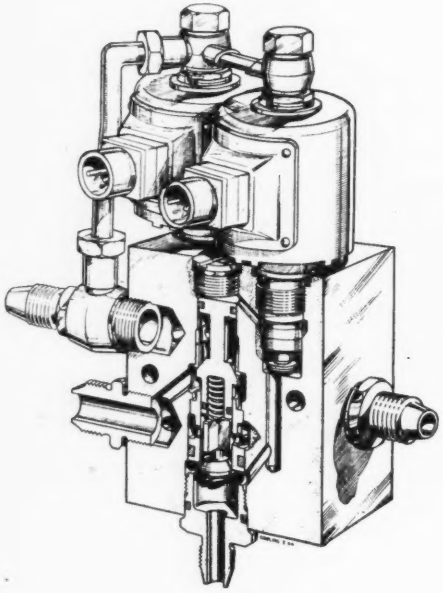


Fig. 49
Dowty Two-way Solenoid Valve.

Remote Control Switches.

Fig. 50 shows a two button switch capable of controlling most services. When intermediate setting of jack travel is required, a multi-button or lever switch is used. These are used in conjunction with a drum switch coupled to the operated unit. See Fig. 51. The lever on the drum switch is mechanically operated to break the circuit when the required jack movement has been obtained, thus closing the solenoid valve.

Thermal Relief Valves.

Thermal relief valves are incorporated to prevent damage to the hydraulic system by expansion of the oil due to temperature increase.

These valves can be incorporated in the jacks and generally consist of small relief-valves, blowing off at pressure in excess of the cut-out or re-acting pressure.

Non-Return and Restrictor Valves.

Many installations incorporate non-return valves, also restrictor valves to reduce the speeds of jack operation. The working principles of these units are well known and need no description.

Pressure Unloading or Cut-Out Valves.

Most hydraulic installations incorporate pressure unloading or cut-out valves to divert fluid from the pump through an idling circuit to the reservoir when jacks are not in operation. The functioning of these valves is well known.

The Dowty Live Line system dispenses with these units as the pump returns to the no delivery position on completion of jack travel.

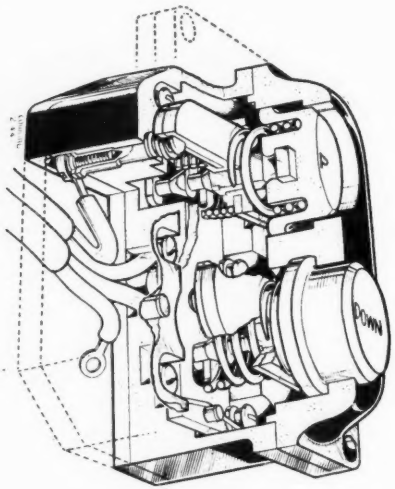


Fig. 50
Dowty Two-button Remote Control Switch.

JACKS.

Hydraulic jacks are made in a wide range varying from undercarriage jacks 6 ft. long to small units for operating fuel cocks and similar auxiliary controls. As the hydraulic

fluid is thin mineral oil the piston seals and the piston rod glands are of synthetic rubber.

It is my opinion that flexible pipes are the weak link in any hydraulic installation. This is based on experience over a number of years.

The jack illustrated in Fig. 52 uses rigid pipe lines but any desired angular movement may take place. This design was evolved to dispense with flexible pipes. The pivot spindle on which the jack rotates is provided with glands and oil passages. The pipes from the

Fig. 51
Dowty Push-button Unit and Drum Switch.

control valves are coupled directly to the fixed pivot pin; one oil way communicates with the cylinder above the piston and the other to a pipe passing along the outside of the jack to the underside of the piston.

This arrangement has proved most satisfactory on thousands of units.

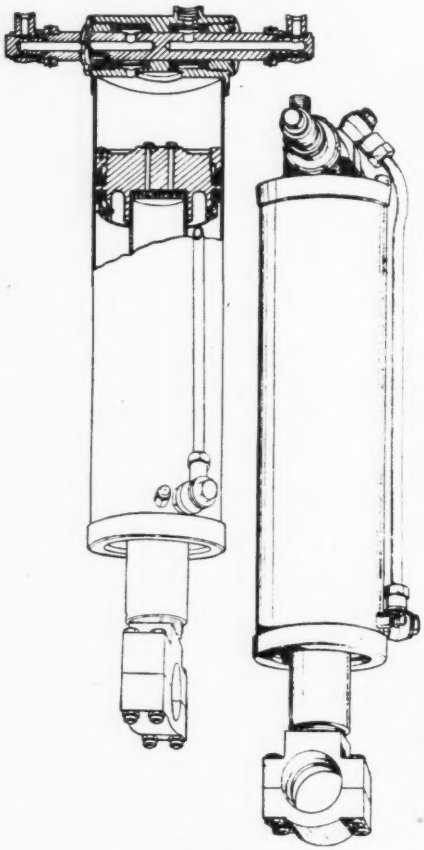


Fig. 52
Hydraulic Jack with Glanded Pivot Spindle.

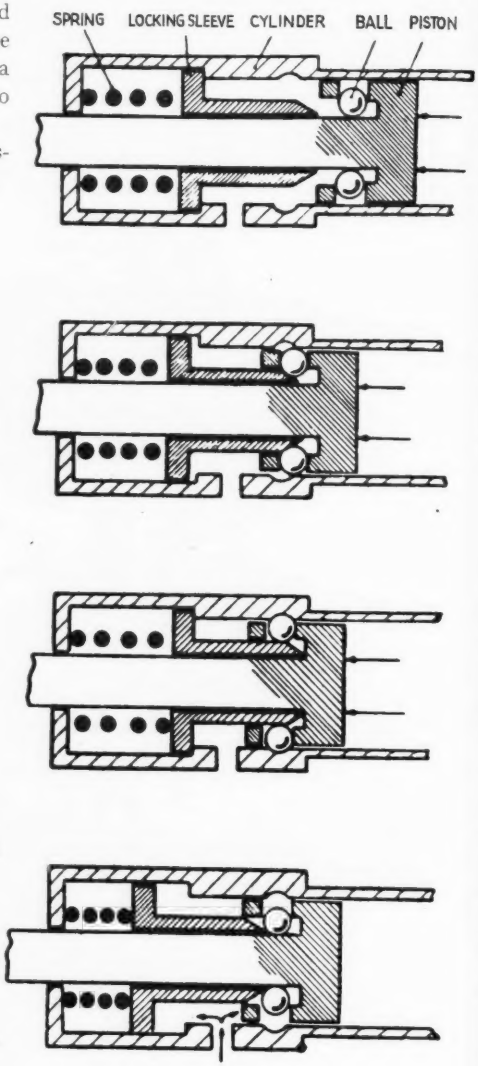


Fig. 54.
Functioning Diagram for Ball-locking Jack.

Fig. 53
Hydraulic Jack with Ball Locks.

Three Position Jacks.

It is sometimes necessary to provide a jack giving one intermediate position between fully compressed and fully extended. This requirement can be met in a number of ways but specially constructed jacks are being abandoned in favour of normal jacks with multi-position remote control already described in this paper.

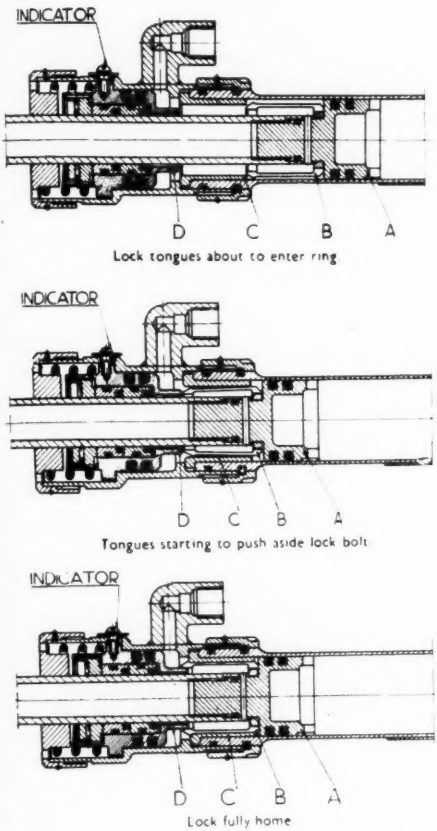


Fig. 55
Messier Claw Lock.

Jack Locking Devices.

Locking is usually limited to undercarriage jacks. This takes the form of ball or claw locks fitted internally in the jacks.

Fig. 53 shows a jack with ball locks, and Fig. 54 the functioning.

Messier have produced a very effective claw lock. Fig. 55 illustrates its functioning.

The piston "A" carries a split ring sleeve "B" which as the jack extends passes inside ring "C." At the end of its travel it pushes back collar "D" and the sleeve tenons spring out over the end of the ring. Collar "D" then moves back into the centre of the sleeve, locking it in the ring. The jack is thus positively locked until oil pressure in the opposite direction withdraws collar "D" allowing the sleeve to contract and the piston to move.

A jack lock produced by Vickers is shown in Figs. 56 and 57. Locking is effected by a number of segments which register with an end fitting and a piston rod collar. The end

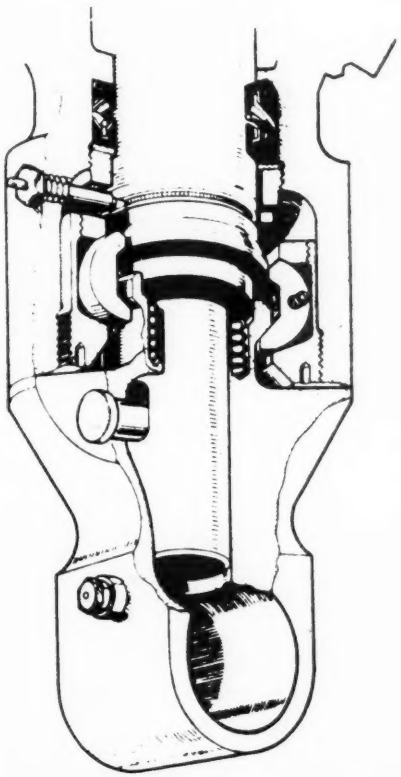


Fig. 56
Vickers Claw Lock.

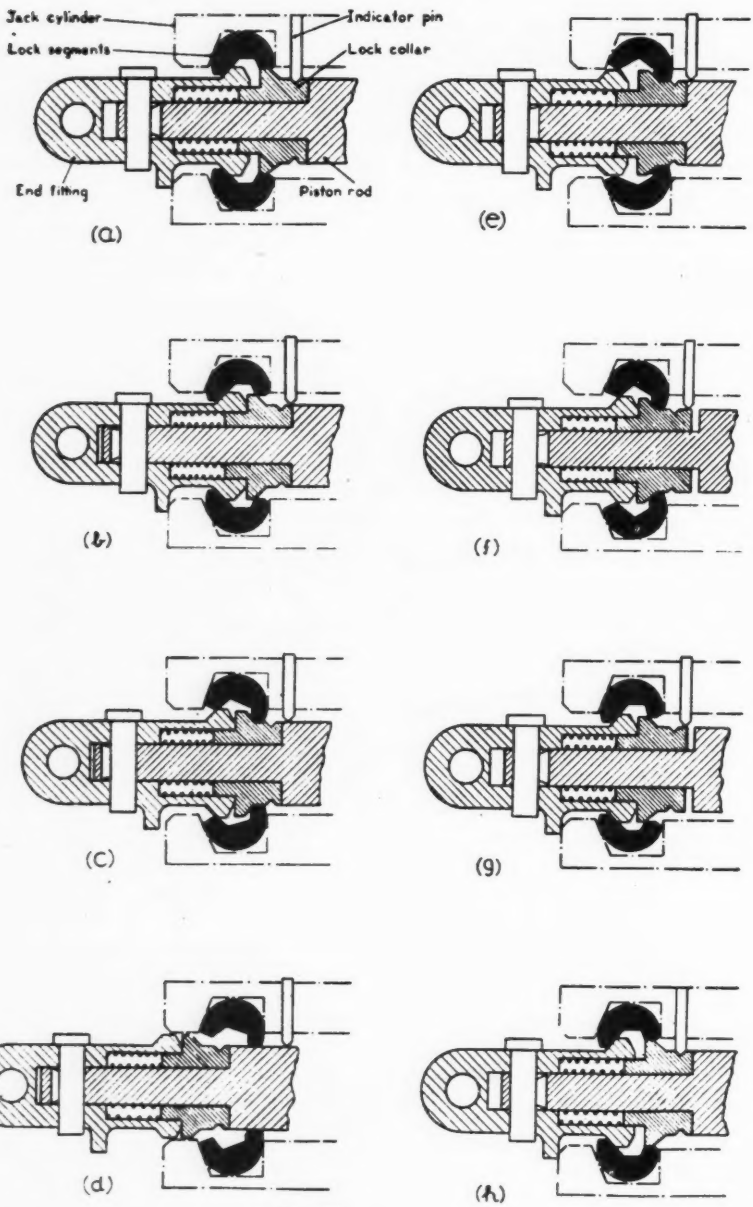


Fig. 57
Diagram of Vickers Claw Lock.

fitting is attached to the piston rod by a pin through a slot in the rod which allows the fitting to move for a short distance.

The lock collar can also move on the rod and is urged away from the end fitting by springs.

Hydraulic locks are sometimes used in flap, bomb door or similar circuits. Fig. 58 shows a section through a two-way hydraulic lock. Oil cannot escape from the jack until pressure applied at one connection of the valve operates a plunger to open the return line.

maximum pressure. "U" section rings are normally provided with a flare to give an interference fit.

Piston head glands are most important, as the cylinder barrel in which they operate is costly to produce. With large numbers of jacks in the circuit, fine limits and high class finishes can greatly increase the cost of an hydraulic system.

Large clearances between the piston and the cylinder wall can result in the rubber packings extruding between the piston and cylin-

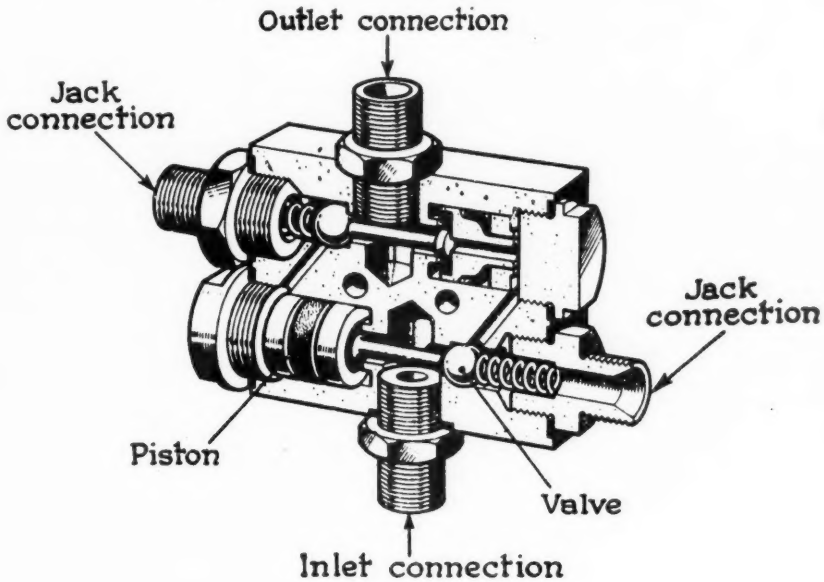


Fig. 58
Dowty Two-way Hydraulic Lock.

Hydraulic Glands.

Hydraulic gland assemblies take various forms. In America those in general use are of the "O" ring type shown in Fig. 59. In this country glands of either "U" or square section are chiefly employed. Square section rings are used for static or piston seals. "U" section rings are principally employed for external glands.

They give low friction and provide perfect sealing under all conditions from zero to

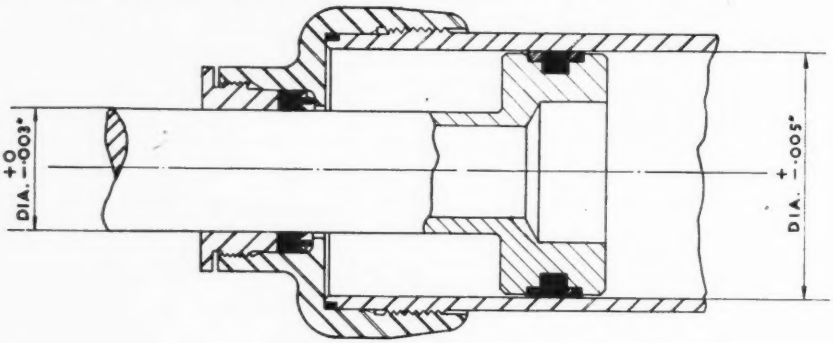
der. For instance, at 3,000 lb. per sq. inch it is not possible to tolerate clearances much in excess of .0005" with normal glanding. In order to permit wider tolerances between the working parts and thereby reduce manufacturing costs, Dowty Equipment Ltd. devised the arrangement employing a metal piston ring (similar to that used on I.C. engines) to back up the rubber sealing ring. This permits the production of a piston and cylinder in which the limits are .005". This system,

now widely employed, has greatly simplified jack manufacture.

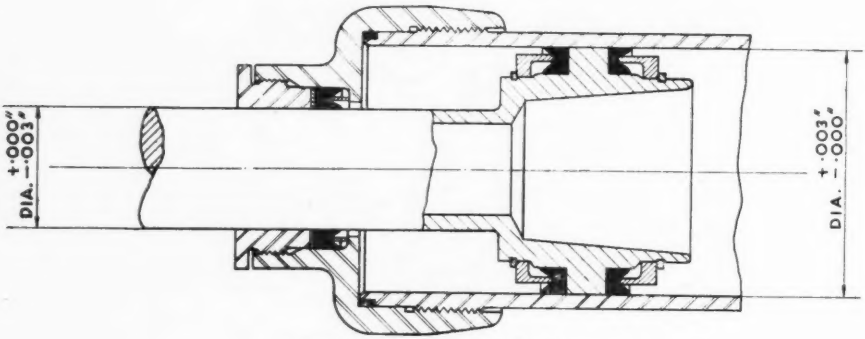
Hydraulic Fluids.

The standardised hydraulic fluids to specification D.T.D.44.D. and D.T.D.585 are light mineral oils. The castor base fluids previously used in some systems are being abandoned.

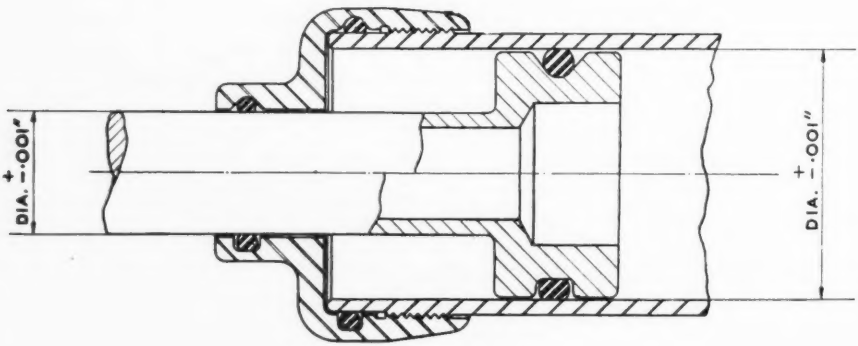
The pour point for D.T.D.44.D. is $-45°$ C. and $-59.4°$ C. for D.T.D.585.



Dowty High Pressure Glanding.



Low Pressure U-Section Glanding.



American "O" Ring Glanding.

Fig. 59

Sections of Jacks showing Various Types of Glanding.

Intava 694 has been used experimentally for very low temperature work and has a pour point of −80° C. Unfortunately at higher temperatures it is little more viscous than paraffin and has poor lubricating properties.

Emergency Systems.

The Dowty emergency system utilises compressed air stored in a bottle. Fig. 60 shows a diagram of this system. Inflation of the air bottle is a ground operation and independent of the engine air compressor. The bottle is provided with a release valve.

During emergency operation shuttle valves mounted on or near the jacks blank off the normal oil supply line and admit air to the jacks. Simultaneously the return line is open to atmosphere.

Some systems employ carbon dioxide or slow burning cartridges in place of compressed air.

Possible Future Developments.

All equipment described in this paper is in use and is available to aircraft constructors, but undoubtedly the future will see further application of hydraulic power in aircraft services.

Hydraulic control and actuation of reversible pitch airscrews offers scope for development.

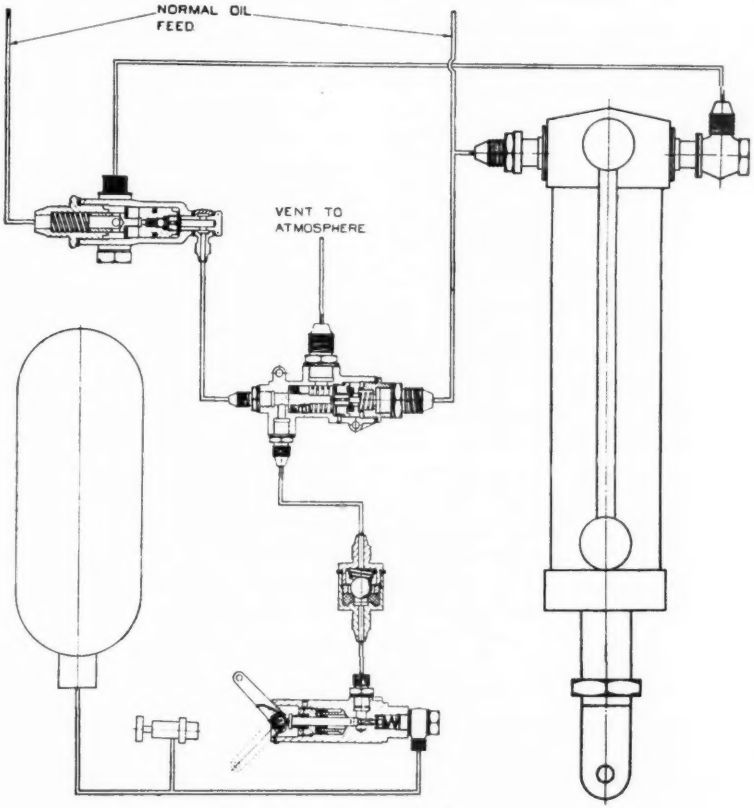


Fig. 60
Dowty Emergency Air System.

Interest is being shown in pre-rotation of wheels before landing, and hydraulic motors could provide the requisite power.

Possibly hydraulic power will be employed on high speed aircraft to retract part of the wing area in flight.

DISCUSSION.

Mr. GOUGE (Fellow), Saunders Roe Ltd., thanked the author for the excellent manner in which he had put forward the case for hydraulics for operating various accessories in aircraft. This paper, coupled with that of Mr. Woodford, would form a very fine basis for designers to compare the two systems. There were, however, one or two points which could be brought out to make the two papers more valuable still. It would be excellent if there could be a weight estimate comparing the two systems for some particular operation. It would also be interesting to know the efficiency of the two systems. As far as he had been able to judge from the paper, the author had not quoted any efficiencies nor were any quoted by Mr. Woodford as regards electrics, but if some figures in regard to this could be obtained they would add greatly to the value of the two papers and enable designers to judge better whether they should alopt hydraulics, electrics, or a combination of the two systems. There was also a further important point which should be brought out, *viz.*, the relative costs of the two systems. Data on this matter would further enhance the value of the papers. From what the author had said and shown on his slides, it would appear that hydraulics were very much simpler than electrics but he would respectfully point out that there was far more to it than the slides showed, as the author was at pains to point out later in the paper when he talked about tolerances and showed a few pumps. It might well be that a compromise between the two systems was the correct answer, although in the past he had always found that a compromise produced a mongrel which very often had the bad points of both and none of the good points.

Mr. F. ROWARTH (Fellow, M.A.P.): Surely it should be possible to acknowledge that there was room for both hydraulics and electrics. Last year he had tackled the chief engineer of the Douglas Aircraft Corporation on this same subject when he was over here, and he said he had an electrics expert and an hydraulics expert and when he had a problem concerning auxiliary services he gave it to both of them, and having obtained a complete picture as regards weight, efficiency and price, he gave the job to the man who produced the best answer. That was an instance of how a completely unbiassed man obtained the best answer every time. Undoubtedly there was room for both systems and it was not wise to be dogmatic.

He was a little sorry that Mr. Bound dismissed pneumatics so lightly because he felt that if it was admissible to discuss the merits of rival systems in a hydraulics paper, then pneumatics should be treated in the same way as electrics. The big advantage of pneumatics, as he saw it, was that it did not drip, and for commercial applications that might be a very real point. There was cost to the designer and cost to the operator and there might be claims for passengers' clothes. On this ground alone, therefore, he did not think pneumatics should be dismissed quite so easily as Mr. Bound had done.

Mr. S. M. PARKER (Lockheeds): It was a very great privilege to support his friend and rival, Mr. Bound, and he was in substantial agreement with all that had been said in the paper. There was one point in the paper which he would particularly like to refer to. From the remarks of the Chairman he gathered it was no accident that there had been papers on electrics and hydraulics at consecutive meetings and he was bound to say he felt that a proper and healthy rivalry between these and oher competitive schemes was a most excellent thing. But he had seen signs at times of this rivalry becoming rather bigoted in argument and that certainly was not in the best interests of the industry. It was the duty of he Royal Aeronautical

Society to prevent that sort of bias and to promote a right spirit of co-operation.

Continuing, he said he would like to make a point which Mr. Bound had not made, *viz.*, that the hydraulic system was very young. It was still in its swaddling clothes and it had been asked to take part in an enormous production expansion, which had not been an altogether unmixed blessing. There had been cases in which development had been retarded as a result. At the same time, he felt that the papers entitled hydraulic engineers to be satisfied but not complacent. There should be no attempt to ignore the difficulties. Some of the primary advantages of the hydraulic system had by no means been appreciated yet, but at the same time he felt that maintenance was far too high. It was not always appreciated, however, that as an industry, hydraulics had faced up to standardisation of and great increases in pressures during the war. This increase in pressures had also had to be met in face of a shortage of rubber, etc., but the industry had always met the difficulties and he hoped they could look forward to a very substantial improvement on the standard already achieved. Mention had been made by Mr. Rowarth of "dripping" on the passengers but it should be remembered that all the pipes were not in the fuselage or where the passengers were. Perhaps there was the choice of drowning the passengers by the use of hydraulics or giving them pneumonia by using pneumatics!

Finally, he asked for opinions on the question of Servo controls. This was a problem which would become increasingly important with new types of aircraft and one which would probably be solved both electrically and hydraulically and, perhaps, pneumatically. Therefore, he asked for definite opinions on that very difficult subject by those qualified to give them.

Mr. H. G. Conway (Associate Fellow, Messier Aircraft Equipment): He thought that certain aspects of hydraulic equipment could not be overstressed. The first was performance—no other equipment got so satisfactory a result, both as regards speed and security. The second was flexibility—they were often called upon to put another jack in here or there to control some new flap or door, and the facility with which this could be done greatly exceeded any other competitive system. The third was a rather overworked phrase—"ease of installation." Electrical enthusiasts usually stressed the attractions of the electrical actuator whose mechanism was all concentrated in one place and was not spread about the aircraft. This, however, was rarely an advantage and the ease with which the hydraulic jack could be accommodated in the airframe greatly exceeded any electric equivalent.

On the other hand to be constructive it must be admitted that hydraulics have faults. In his view the sooner the hydraulic engineer admitted them, and did something about it, the better. One had a tendency to be too clever and to solve problems hydraulically that should be done by some other means. There was hardly ever an excuse for hydraulically operated undercarriage doors with their attendant sequence valves. In America they had even now proposed hydraulic fuses.

There was much too much piping in any but the smallest system and electro-hydraulics was an absolute essential on any new design.

Hydraulic components were too sensitive to the swarf and dirt that the airframe factory insisted on leaving in the pipes. The components must be made less sensitive to this dirt as it was apparently useless to try and have the dirt eliminated.

Even the simple pipe connection needed improvement; the A.G.S. type was too expensive and difficult to fit—other types were too sensitive to bad handling.

In spite, however, of these faults, hydraulic equipment had given remarkable service during the war, and given greater opportunities for development and improvements in the percentages of skilled labour in the factories; peace time will bring equipment which performance for performance will not be beaten by any other system.

He wished to make two final points:—

Pneumatics were dangerous owing to the energy stored in the compressed air. A pneumatic pipe or jack could explode with serious consequences.

Power flying controls were priority items of development. Hydraulic solutions were practicable and in production—that was more than any competitor could claim.

Results recorded with several hundreds of thousands of high pressure flexible pipes indicate that they were far more reliable than any rotary gland device.

The author mentioned very fine clearances necessary between cylinder and piston in the case of the hydraulic jack, but his experience with a hundred thousand jacks indicated that clearances of three or four thousandths of an inch gave no trouble at all.

With regard to Mr. Gouge's request for comparative figures on the weights of hydraulics and electrics, it was interesting to recall the results of an investigation carried out by the S.B.A.C. Committee some time ago. The actual electric undercarriage system on the F.W.190 aircraft was weighed and analysed. An alternative hydraulic system based on equipment in production for a British fighter was then designed and was estimated to weigh 80 lb. as compared with 130 lb. for the original system. The Electrical Engineers came along and said that the F.W.190 was badly designed and that they could produce a system for 70 lb.

Mr. C. G. A. Woodford (Associate Fellow, English Electric Co. Ltd.): He was the very last person in the world, as he had indicated when his own paper was discussed, to enter into a war between electrics and hydraulics. That had never been his intention and he was very pleased to see the extent to which the improvements in hydraulics, which the author had indicated, were taking advantage of the contribution that electric power could make to hydraulic operation. As an electrical engineer he had quite an open mind as to how electricity should be transferred into mechanical effort at the point of application—whether by oil in a pipe or cylinder, or by gears in a box. At the same time, he did not think it was useful to compare the two methods from the point of view of application to a single function. What mattered was the complete installation throughout the aeroplane, and if considerable savings could be achieved by the use of light weight equipment for ancillary purposes in the future, it mattered little how the electrical energy was transformed into mechanical energy at the point of application. That was probably the answer to the general problem.

Discussing one or two points in the paper, Mr. Woodford first mentioned the reference by the author to the relative difference of speed between the source of power and the application. He said that it was quite a normal method in many forms of power transmission to step up by some high speed link for the transmission in between. That was often the best way of meeting transmission requirements.

He was glad electro-pneumatics had been mentioned because he was rather hoping that electric power would play a leading part in this connection as well as in electro-hydraulics.

As to the relative complexity or simplicity of electrics and hydraulics the comparison shewn by the author of a more or less complicated electrical actuator and just a simple hydraulic piston had been made several times before, but the author in all his other slides had destroyed any illusion that it was enough to compare just the actuator. It was the whole system which really counted and he believed the point was still valid that whereas the complexity of electrics, if it were done by mechanical gear, could be concentrated in the actuator, in the case of hydraulics, it was distributed over a very large part of the aeroplane and the author's comparison in that one slide did not indicate anything like the complexity of hydraulics. In reply to discussion on his own paper he had indicated what the two systems looked like for a particular service and Mr. Bound had added to that by showing how the complete hydraulic system could be very much cleaned up by electrical transmission

throughout the aeroplane. As time went on, he believed there would be rather more electrical transmission than electrical solenoid valve control of the hydraulic pipe system. It was the pipes and valves that should be eliminated.

Then there was the question of the efficiency of transmission. He did not know what the over-all efficiency of transmission of the hydraulic system would be throughout the aeroplane, but it might be about 50 per cent. The corresponding efficiency of the electric system would be at least 90 per cent. and that would indicate a reduction in the power required in a local electric pump, which also would run only when needed. Some of the pumps which the author had shown in his slides rather reminded him of the picture of the electric actuator which had also been shown, so far as complication was concerned. The author had mentioned the use of a standard low voltage electrical system for valve operation but that would not rule out the use of a high voltage lightweight system where the need for it arose.

He was not quite clear as to the effect of increasing rotational speed and raising the power output, without increasing the weight and size of the pump, and he would like some idea of the speed of centrifugal hydraulic pumps.

Discussing installation questions, he said it was much easier to run cables than pipes, and the efficiency was not reduced if there was a sharp kink in a cable. Moreover, they did not freeze and they did not squeeze out the copper at high altitudes.

As to possible future uses of hydraulics, there was, as the author had indicated, some interest in the question of pre-rotation of wheels; if that were to be done by hydraulic motor, why not use hydraulics for the brakes at the same time?

With regard to the comparison of hydraulics and electrics, as mentioned by Mr. Gouge, he reiterated that any comparison must be on the basis of the whole aeroplane and not of any one operation. Only in that way was it possible to get the answer to the most important question now being faced.

Mr. R. H. Chaplin (Fellow, Hawker Aircraft, Ltd.): Perhaps it was inevitable that a paper of this kind should open the old controversy of electrics versus hydraulics. He was very glad the author had expressed the view that a judicious mixing of the two systems would produce the best result. Personally, he heartily endorsed that view, and could not see any reason why it should not be done quite efficiently. At the same time, he could not see how the electric actuator could compete with the simple hydraulic jack when a simple linear motion between two positions was required.

There were two conditions in which electric actuators were preferable. One was where the three-position actuator was required, particularly where the mid-position must be adjustable, and the second was where the actuator was controlled by a thermostatically operated electric relay, as used for the control of a cooler flap. But having introduced electrics into the operation it seemed silly that hydraulics should be brought back again, as this could only be done through the solenoid valve. It was true that both the conditions he had referred to could be satisfied by hydraulic actuators, but, he submitted, not so satisfactorily as by electric actuators. He was sorry to see Mr. Bound had seriously considered the use of the electro-hydraulic type. That might be good on future larger craft but he doubted whether the elemination of the control valve and the reduction in pipe lengths would pay for the extra weight of the electric motor and also the notorious unreliability of electric motors in close proximity to oil. There was also need to be careful about the adoption of the solenoid operated valve. Its use was justified when sequence valving was required but solenoids were heavy and this should be considered carefully before deciding on their general use.

As regards cavitation, the only satisfactory method of dealing with this was the pres-

surisation of the system, which he could confirm from personal experience did not give trouble.

With regard to pre-rotation of wheels, this did not seem to be necessary on evidence, and he recalled that Mr. Wright in his recent lecture had stated that such methods were unjustified.

Another important development not mentioned by the author but referred to by Mr. Parker was hydraulic power operated servo flight controls. They were likely to be required both on very large moderate speed aircraft and also on small aircraft which were approaching the speed of sound, and should certainly be included in Mr. Bound's list of future developments.

Reference had been made to the relative efficiencies of the electric and hydraulic systems but personally he did not think that the efficiency of the system was important. Weight, simplicity, reliability, maintenance and cheapness were much more important. The power required to operate the system was so small that it did not seem to him that efficiency was very important. He did not agree with Mr. Conway that flexible pipes were satisfactory. That might be the case if the pressures were low enough, but at the pressures referred to by the author which had been in common use for some time, definitely No.

Mr. T. S. DUNCAN (Vickers Armstrong, Ltd.): In hydraulic systems there were too many valves and the systems were very complicated. We should have motor driven pumps and remote controlled valves, the hydraulic principle being used solely as a reducing gear of high efficiency and as a means of coupling the high speed of the pump with the slower moving ram of the undercarriage.

He agreed with Mr. Chaplin that flexible pipes were unsatisfactory. We should avoid pressures above 2,000 pounds per square inch as this was regarded as the limit for servicing.

Mr. P. W. S. BULMAN (Fellow, Hawker Aircraft, Ltd.): From the pilot's point of view, he was reminded of an unofficial census of the American industry on this particular subject some years ago. He believed he was right in saying that those firms which used electrics preferred hydraulics and those with experience of hydraulics expressed a unanimous preference for electrics! With previous speakers, he had been impressed by the diagram of the hydraulic jack shown by the lecturer with its obvious simplicity when linear motion was required. It took his thoughts back to the U.S.A. and the Empire State Building, where a 1,000 ft. stroke hydraulic ram seemed just the thing for the elevators.

However, he was glad to see that the lecturer as well as other speakers had a little feeling for the maintenance man. In his opinion neither designer or user minded very much which system was used so long as the apparatus was easy to install and was trouble free in service. There were no doubt plenty of excuses for unreliability in war time, but he believed that attention paid to this matter would be well repaid by the wider or universal employment of that system which proved the more reliable.

Mr. E. W. DOUBLE (Rotax Ltd.), said there were two points which he would like to emphasise. The first was that a fair comparison between hydraulics and electrics could not be made until a given type of aircraft had been fully equipped with both forms of auxiliary power. When this was done, operational data together with information on cost and maintenance would be available. Even so it should be remembered that one form of power might be more suited for one type of aircraft than for another, and at this stage no firm ruling could be made.

The second point was that there was an important factor in favour of electrics which had not perhaps been brought out or sufficiently stressed in the discussion so far. It applied particularly to large machines, especially civil types. These aircraft would obviously have to be equipped with electrical

plant for the supply of such services as radio, lighting, heating, cooking, and de-icing; the power needed for these services would increase the size of the aircraft. Hence why not make full use of the electrical plant for the operation of those services now effected hydraulically, and so instal only one instead of two forms of auxiliary power? The normal advantages of electricity were well known and if they were given full scope either in typical or in experimental machines, then in his view the aircraft manufacturers would have no regrets.

It might well be as Mr. Bound and others have indicated, that certain services, for a time at any rate, would be operated by a marriage of hydraulic and electric power, but the potentialities of the latter now seriously challenge the former.

Mr. W. H. CAMPBELL (Metropolitan-Vickers): Speaking as a visitor and an electrical engineer he said that in spite of the very fair outlook which the author developed later in his paper, he started off with some rather sweeping generalisations about electrics. The easy comparison between a hydraulic cylinder and its piston, and the electric actuator, shewn by the author in one of his slides, was being used widely by the hydraulics industry in selling their wares, but it was useful to remember that the principles involved in the electric motor were, perhaps, just as simple and could be illustrated just as simply as in the case of hydraulics. One might have shown a slide of a simple magnet with some indication of the field which it created, and a clean straight wire indicating how the passage of electricity produced linear motion, but it would be altogether fallacious to produce such a sketch and claim that it indicated the problems involved. Likewise the picture of a simple hydraulic jack gave no indication of the maintenance problems which arose from the inherent difficulties of designing oil-tight glands and pistons without great sacrifice in efficiency and useful life, especially for high pressures of the order of 2,000 to 3,000 lb./sq. in. Similar problems were also present in the design of pumps and valve gear. However, in spite of his early notes about the application of electrics, Mr. Bound went on to admit their use in driving his rather complicated hydraulic equipment, which suggested that he may have had his tongue in his cheek when he wrote the early part of the paper.

Concerning the emergency operation of electric actuators, he said the ball bearing screw and nut for use in the electrically operated jack was in an advanced state of development. It had an efficiency of the order of 90 per cent., and was reversible. It could therefore include a pneumatic scheme of emergency operation, either from the separate air bottle shown in the author's slide or by using the air already available for the brake system.

Mr. Bound had referred to the improved performance/weight ratio of the hydraulic system when using high pressures and electrically driven pumps, but some part of that improvement was probably due to the very fact of using electric pumps with their attendant savings in weight.

Generally, he said he agreed with previous speakers that dogmatic statements concerning the use of hydraulics or electrics for a given purpose were irrelevant and it was hoped that aircraft designers would give fair consideration to both systems. He also agreed with Mr. Double when he said that true comparison could be made only when two aircraft were equipped, one completely electrically and the other with hydraulic actuators. Electric power was essential on the aircraft for many purposes and, that being so, a saving in overall complication and sometimes a saving in weight could be effected by the exclusive use of electricity, but this could not necessarily be shown if only one hydraulic operation were converted to electric drive.

Mr. R. H. CHAPLIN (Fellow, Hawker Aircraft Ltd.) recalled that earlier in the discussion he had expressed surprise that the author should advocate the electric pump and his statement was immediately followed by Mr. Duncan, who had said it was a mar-

vellous thing. He would like the author in his reply to give a justification for its use.

Mr. W. G. LISLE (Fairey Aviation): Whilst the author had covered the subject very thoroughly, he would have liked more comment on the question of servo control as applied, say, to flying controls. As others had mentioned, we were now reaching the stage when there would have to be power operated or power assisted flying controls, especially on very large aircraft, and it would seem that the hydraulic medium was a very suitable one. A simple valve of the "follow up" (sometimes confused with the original pre-selective) type might be used. This was a very simple unit which could be efficiently applied for servo power. One argument often brought against this type of control was that it necessitated the complete absence of what pilots refer to as "feel" in the controls. This was not essentially so, however, as it was possible to transmit a proportion of the actual control load to the pilot's control member, resulting in a reduced "feel" of the orthodox order. This might mean re-educating the pilot, but this in itself did not justify rejection of the method. Another notable use for hydraulics was a specialised application in cases where it was desirable to have what was termed synchronous control, as for example in aircraft flaps where a number of surfaces might be required to move in almost perfect synchronisation. Here the same simple type of valve he had already mentioned could be used to advantage. With such a valve it was possible to obtain an infinite number of positions, generally a very desirable property in such a system, and synchronisation and control could be readily effected by mechanical or electro-hydraulic means. In general, it appeared to him that where one wanted power, hydraulics should be used, and where remote control was desired, electrics should be adopted.

Mr. A. C. BARNES (contributed): He suggested that the lecture would have been more enlightening had Mr. Bound set out to explain distinctly the difference between earlier types of system and current types, with some intimation of possible future trends. As it was, he felt that he probably left the lesser initiated in a state of misapprehension at the various types of pump, control valves, etc., which they may well have thought were current types, whereas a large percentage are in fact obsolescent. A typical layout of a modern system showing the relatively small number of components actually used would, he felt sure, have been of great value in promoting interest in hydraulics.

The expression that some services could best be operated electrically, others hydraulically and others pneumatically was generally accepted, but the suggestion that electro-hydraulic actuation is always the best compromise was debatable, particularly when it was done by means of self-contained units adjacent to service to be operated. More consideration might be given to hydraulic remote control of valves through capillary tubing or the like.

Mr. Bound's scheme for electrical control of hydraulic valves tended to convey the impression that solenoids were accepted as the obvious and best way of operating the valves. This view was not, however, altogether accepted in the industry.

With regard to hydraulic pumps, Mr. Bound stated that pressures which were now being adopted with 2,000/2,500 pounds per square inch precluded the use of gear pumps; this, however, was not the case. There were at present four versions of hydraulic pumps conforming to latest requirements in respect of operating pressures, two of which were illustrated by the lecturer, but one of the remaining two was a gear pump which generated a pressure of 2,000 pounds per square inch by an arrangement incorporating one small reciprocating piston and a simple automatic cut-out valve, a characteristic similar to a variable delivery piston pump is achieved. This pump was relatively simple to make, the clearances quite nominal, and although its overal efficiency at 2,000 pounds per square inch was only about 55%, it com-

pared not unfavourably with the Live Line pump and at the ultimate cut-out pressure of 2,500 pounds per square inch was quite satisfactory in this respect. Since the period during which high pressure and high delivery was required was very short, this efficiency was, at all events, not of great importance so long as the pump was not driven by an electric motor, reliability, which was extremely good with gear pumps, being of far greater importance. Incidentally, other high pressure gear pumps have been developed both in this country and the United States.

The author mentioned two methods of ensuring adequate flow of fluid to the pump at low barometric pressures, but although sound in principle they were not always practicable and there were at least two alternatives, one of which had been tried successfully while the other was being developed at the present time, namely, suction boost by induction from the return line to the reservoir, and a simple gear pump/motor combination across the suction to, and delivery from, the engine driven pump.

He would also like to refer to the statement by one of the speakers that thermostatic control should obviously be done electrically. A fully hydraulic thermo control valve had recently been developed, and the results were very promising. This unit was, he thought, without doubt considerably lighter than the corresponding electrical device.

Finally, current pneumatic systems for brakes, etc., were operating at 450 lb./sq. inch, not 200 lb./sq. inch as stated by Mr. Bound, and systems of 850 lb./sq. inch were being developed. Further, although the majority of Service aircraft at present used pneumatically operated brakes, one big air line user was demanding hydraulic brakes, which were in course of development.

R. F. WORLEDGE (Integral Ltd: contributed): The first point he felt he must raise concerned Mr. Bound's statement that gear pumps were not of any use for pressures in excess of 1,500 lb./sq. inch. At his firm they had at the moment in production a gear pump having two stages, which was operating quite successfully at a working pressure of 2,000 lb./sq. inch, and in conjunction with this pump they used a control device which gave an off-load condition wherein the gear pump circulated freely, and the supply line was kept charged at a pressure of 2,500 lb./sq. inch. This surely met all the conditions at present claimed for piston pumps operating within the same pressure band.

He was left with the impression that where thermostatic controls were required, Mr. Bound's opinion was that this problem could best be solved electrically, and he felt that Mr. Bound could not have been aware of the fact that a thermostatic control operating hydraulically was now in the early production stages, giving perfect results without the use of electrical devices, and which had a sensitivity coupled with lightness of weight which he felt could not be equalled by an electrical alternative. He found Mr. Bound's opinion on this point rather startling, since he rightly affirmed that where the load is heavy, hydraulics are unquestionably the best and, therefore, if one considered that the thermostatic control of a device was to be electric, and the load heavy, the sequence which resulted was the determination of a desired function by thermostatics, the conversion to an electrical impulse, a further conversion to a hydraulic operation and the final conversion to a mechanical adjustment.

One final point which he felt should be mentioned was that by no means all the hydraulic industry were of the opinion that solenoid valves were the answer to the problem of remote control of main hydraulics. He fully agreed with Mr. Bound that it was one method of solving the problem, but remote control of hydraulic valves by hydrostatics was one of the alternative methods which could give equally satisfactory results. It could also compete with the electric devices, since, as no appreciable flow was required, the pipe lines to the servo control in the pilot's cockpit could be extremely small, and as easy to instal as an electric cable.

Finally, he hoped in the future to see Mr. Bound take a more bellicose attitude towards the "Electric Camp," since whilst co-operation on certain aspects must always be possible, a little healthy competition was to the technical advantage of both electrical and hydraulic development.

Reply to the Discussion.

Mr. BOUND: To deal adequately with all the questions and criticisms would take him very much longer than the time available but he would deal with the most important ones. Mr. Gouge said he would be interested to have some weight estimates and efficiencies of the hydraulic system but there had been shewn both in tabular and graphical forms not weight estimates but weights ascertained from low and high pressure systems, and he had hoped that that would have met the point. With regard to efficiencies, he could only agree with Mr. Chaplin that whether 60 or 70 per cent. efficiency was being obtained from the installation did not matter very much when the total H.P. being used was so small, and if all the merits of the system were weighed against any possible reduction in efficiency. If the H.P. was 40 or 50, then he would be more interested to know whether the efficiency was high or low. With such low H.P., however, he would prefer to consider the efficiency of operation and maintenance and satisfactory functioning.

The belief that there was room both for hydraulics and electrics had been mentioned by Mr. Rowarth, and special mention had been made of that in the paper. A number of other speakers had touched on the same point and to avoid dealing with it in each case he would say now quite definitely that he thought there was room for both. One speaker had said that as there had to be a generator for other purposes, why not do everything else electrically? It was said that one could not do cooking hydraulically or work the radio in that way. But there were a good many things that could not be done electrically on an aeroplane. One might compare a modern aeroplane with a modern residence. It was necessary to have electricity, water supply, drainage and various other things; you do not try to do everything on one system. In the same way, there was room for electrics and hydraulics on an aeroplane. Mr. Rowarth had been rather unkind when he said that pneumatics did not drip, but neither did hydraulics. In any case it was not proposed to have the drips falling over people's clothes and as would have been seen from one of the slides no hydraulic pipe was taken in the cabin at all. Moreover, when pneumatics "dripped," it was not possible to know there were drips until it was too late!

Mr. Parker had said that hydraulic people should not be bigoted, but personally he did not think they were, and he could only repeat his view that there was room for everything. Nor did he think those who advocated hydraulics were complacent just because they were fairly well satisfied with what had been accomplished. This much he could say: he still had to earn a living!

Mr. Conway had expressed the view that pneumatics were dangerous. He agreed, having seen some very unpleasant things happen with pneumatic units at high pressures. Nevertheless, he felt that pneumatics had their field of service such as for the very rapid operation of bomb doors when it was necessary to get practically instantaneous operation, both for opening and closing. That could possibly be done better with pneumatics than by hydraulics. He agreed there was room for improvement in pipe connections with hydraulics. As a matter of fact, he had seen some very clever designs but had not been able to obtain permission to refer to them in the paper. However, he was quite convinced that there would be some much simpler and equally efficient yet cheaper pipe connections on the market before very long. Probably progress had been hampered somewhat in this field owing to the need for standardisation and mass production during the war.

Mr. Woodford referred to the part which electricity plays in modern hydraulics, and he himself, like Mr. Woodford, did not agree there was a war between electrics and hydraulics. He repeated that both could be developed to the mutual advantage of the aircraft constructor and designer. Mr. Woodford had also stressed the advantage of transmission at high speed, but frankly he did not see the point there. What was the advantage? Why take the trouble to run something very fast when the final operation was relatively slow? He had endeavoured to put that in a concise form at the beginning of the paper, but he might not have covered Mr. Woodford's point. Mention had also been made by Mr. Woodford of the distribution of the parts of an hydraulic system all over the aeroplane, but if Mr. Woodford had been frank and had shewn a diagram of the many fuse boxes, switches, etc., on an aeroplane fitted with electrics, it would have been seen there were quite a lot of electrics spread over the aircraft. It was possible to concentrate hydraulic units, as had been shewn on one of the slides. It was also pointed out that there were seven different types of valve—which there had not been time to deal with in detail. He had only described the types of unit developed during recent years and which were available. Surely Mr. Woodford did not imagine there were seven different types of valve in every installation? Naturally the most suitable one for the particular job was selected. He was not very clear as to Mr. Woodford's point concerning the efficiency of pumps. His reason for saying that a higher H.P. was absorbed by running the pumps faster was merely because obviously a higher H.P. would be required to deal with the very much heavier undercarriages on larger aeroplanes, and he had put that in the paper in order to suggest that if the r.p.m. was increased, a greater output in H.P. could be obtained from the pump without increasing the size. Mr. Woodford also said that electrics did not suffer very much if there were kinks in the cables, whereas kinks in pipes were serious. In the paper he had endeavoured to shew that the system of the future would have the minimum of piping, especially if electrically controlled solenoid valves were used, and if there were short pipe runs to the solenoid valves and on to the jacks, there would not be pipes the length of the fuselage to the pilot's cockpit and back again. Hydraulic brakes had also been mentioned by Mr. Woodford, but unfortunately he was not at liberty to say as much on that subject as he would like to. Quite obviously, hydraulic brakes would be developed which would be very efficient and they could be tapped off the normal system. It had been done before. It was done on a number of machines in this country a few years ago and he believed the pendulum would swing in that direction again.

Mr. Chaplin had referred to the three position jack and expressed a preference for doing it by means of an electric actuator. Maybe Mr. Chaplin was right, but it was quite simple to provide a three-position hydraulic jack operated purely hydraulically or, as suggested in the paper, to have some sort of switch on the normal jack controlled by a pre-selector lever. He was surprised to hear Mr. Chaplin say that we should be careful about the adoption of the solenoid operated valve. There had been considerable experience with these and there had never been any trouble. As to these valves being heavy and bulky, it must be remembered that their use resulted in the elimination of pipes containing oil which would normally run to a manually operated control valve, and considerable weight was saved in that way. With regard to what Mr Chaplin said concerning the pre-rotation of wheels and the fact that Mr. Wright had said there was no point in this as it did not seriously affect tyre wear, there was another aspect which must not be overlooked; pre-rotation of the wheels before landing added to the efficiency of the shock absorbers, and particularly the telescopic type of shock absorber, by reducing the drag component on touch down. With regard to hydraulic flying

controls, a great deal of work had been done on that subject but he had endeavoured to confine the paper to items of equipment that had been in use for a considerable period of time and which, therefore, he felt he could speak about with some authority. He had not gone into new hydraulic controls for that reason.

Mr. Duncan had expressed a hearty dislike for hydraulics but he would ask him to look again at one of the slides which shewed the pipe lay-out. He was also surprised to hear Mr. Duncan say that 2,000 lb. should be the maximum operating pressure because personally he had had experience of pressures far in excess of that and he believed the only reason why it was not advisable to go even higher was that it was not economical from the jack point of view. He would not hesitate to go to 5,000 lb., and would not be worried about glands or pipe joints.

He was interested to hear Mr. Bulman's comments on maintenance because 8 or 9 years ago Mr. Bulman had given him a piece of advice which he had remembered and passed on to his design staff. He said that in an hydraulic installation one should put a handful of sand in the reservoir and then see that it kept working. That was good economics because in the desert, sand blew in and eventually got into the reservoir and therefore filtration had been provided on the majority of hydraulic installations to-day.

Mr. Double said he was biased towards electrics. That was unfortunate; personally, he was not biased either way. He tried to find a solution for all problems as they arose. Mr. Double had suggested that as there was a generator on the aeroplane it should be used for everything. That point had already been replied to. Perhaps in a few years electric actuators woud be developed and produced in large quantities and he would then probably be equally interested in electric actuators.

Mr. Campbell also had complained of the comparative diagram of the electric actuator and the hydraulic jack and had suggested it would have been fairer to have shewn a simple diagram of the magnetic field. But the hydraulic jack was shewn as a complete engineering job with the cylinder, piston and gland, and the electric actuator was shewn with its motor, clutch and gear box. As a matter of fact, if he was being at all unfair, he was unfair to hydraulics because the electric actuator as shewn on the screen gave a rotational motion that still had to be translated into linear motion by means of a worm or shaft or something of that sort, whereas the hydraulic jack gave the final linear motion that was required. The same speaker also mentioned emergency operations and suggested that the air in the brake system should be used for this purpose. That, however, was absolutely out of the question. The air in the brake system was at about 200 or 250 lb. pressure whereas the hydraulic system was working at 2,000 to 3,000 lb. pressure, thus the air in the braking system would be totally inadequate for emergency operations. The point made with regard to the graph shewing the improved performance/weight ratio of the hydraulic system was not quite correct. The graph in question shewed the weight saving over a low pressure system by a modern high pressure system with solenoid operated valves, and not electrically driven pumps.

Mr. Lisle referred to servo controls, but again he had to say that the paper dealt only with equipment that had been in use for a long period. A paragraph might have been included on future possible developments. Mr. Lisle had also referred to what he termed synchronous control, but the type of valve he had mentioned was not new. His own company developed them for use on hydraulic systems many years ago but they now felt that their more recent introduction of the jack with the solenoid operated valve and drum switch was the better solution.

SOME NOTES ON VIBRATION ANALYSIS

by

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He has published numerous papers on Vibration Theory, including four in the Journal, and his work on Waveform Anaylsis is now in the press.

1. Introduction.

The general recognition of the importance of vibration study, as a specialised branch of engineering science, is clearly reflected in the fact that each year sees the publication of a great number of papers on all aspects of vibration theory and practice. The theoretical papers most commonly describe new methods of analysis and calculation, and it is becoming increasingly difficult for the general engineer, who has neither the time nor the inclination to follow in great detail the development of all the specialised subjects, of which vibration study is only one, to retain in his mind a clear picture of the general strategy applicable to the attack on vibration problems, and to fit into this strategical scheme the tactical operations represented by the new methods.

The object of these notes is to outline the fundamental process of solution of vibration problems, so far as this is affected by calculation, rather than to advocate or expound any new technique. That is to say, the subject matter is strategy rather than tactics. At the same time, they may serve to remind the evergrowing body of students of this subject that in many problems a useful solution can be obtained more speedily, and with a greater likelihood of correct interpretation, by straightforward analysis than by the use of some highly developed special technique.

The author has described elsewhere* the physical nature and background of vibration problems in aeronautical engineering, and is here concerned with the processes of calculation. In calculating, say, the vibration stresses in an engine crankshaft, the mathematician and the engineer are likely to proceed by entirely different routes to the same end. In particular, the engineer often prefers to make use of " natural modes " and " dynamic magnifiers" in calculating the response to a set of applied forces. The connection between these quantities and the formal solution to the ordinary equations of motion, as a set of

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* " Vibrations in Aircraft," Aircraft Engineering, Feb.-May, 1944.

simultaneous equations, is by no means as clear as it might be even to a mathematician ; and since at least one standard work on the subject is silent upon this connection, and gives no justification for the technique normally employed, it may be assumed that not everyone who employs the technique is aware of the fact that its validity can be demonstrated by an extension of the straightforward analysis. The proof is outlined in the Appendix.

A simple numerical example is treated in both ways, to illustrate the general descriptions in the text.

2. Aim of Analysis.

It is required to determine the response of the vibrating sytem to a combination of applied forces. It is known that this response depends, in any particular case, upon the frequencies of the applied forces, and it is therefore necessary to calculate the response over a wide range of frequencies relevant to the problem.

In engineering the main object of vibration research is the avoidance of serious resonant conditions. For every structure or machine there is a certain number of frequencies at which it will tend to vibrate when deflected or disturbed from its position of static equilibrium, and these are termed *natural frequencies*. It is found that very large vibrations can occur if the structure is " excited " by a vibratory force whose frequency is the same as one of the natural frequencies, and this is the condition of " resonance." Since in general the dynamic stresses in various parts of the assembly are proportional to vibration amplitudes, the resonance condition is to be avoided in the interests of safety ; and in aircraft engineering the necessity for the strictest economy in weight, which calls for the minimum effective factors of safety, emphasises still more strongly the avoidance of resonance. In many cases, however, and particularly in aircraft engineering, the dynamic stresses in non-resonant conditions also can be of great importance.

Consequently it is very helpful to derive graphs showing the magnitude of stress in various parts of the assembly, over a frequency range covering the characteristics of the various sources of excitation.

3. Preliminary Analysis.

For the purposes of calculation, the actual vibrating system is replaced by a combination of idealised elements, of three types :

(i) inertia elements, opposing deflections with forces or torques proportional to the acceleration of deflection ;

(ii) spring elements, opposing deformations with forces or torques proportional to the deformation (extension, compression, twist or flexure) ; and

(iii) dissipative elements.

In practice, the effects of damping forces are not usually taken into account, as their inclusion greatly increases the difficulty of the analysis, their omission does not usually appreciably affect the accuracy of the calculations except by giving a too pessimistic view of the stresses in resonant or near-resonant conditions, and it is known how to allow for this omission in the interpretation of the final results ; dissipative elements are therefore disregarded in the following.

The correspondence between the parts of the material system and the elements of the idealised system is not necessarily one-to-one. Thus, for example, if two springs in parallel connection are so constrained that they must always suffer the same deformations, they are equivalent to a single spring and will therefore be represented by a single spring element ; and a single massive body may require to be represented by no fewer than six inertia members, three to account for its mass effect in linear

displacements and three for its inertia effect in rotations. The case in which a given part of the system requires to be represented both by an inertia element and by a spring element, e.g. in a heavy cantilever beam, falls outside the scope of these notes. By far the greater part of the vibration problems of general and aircraft engineering concern systems which can, without distortion of essentials, be represented by an idealised system of rigid masses and massless springs.

Displacements of the system from the position of static equilibrium are represented by generalised co-ordinates. These are independent in the sense that it is physically possible to vary any one alone without violating the geometrical constraints, although of course it may happen that such a variation deforms spring elements. For example, in a torsional system comprising two inertias joined by a flexible shaft, the generalised co-ordinates may be the angular displacements of the inertias, independent variation of which is physically possible but twists the shaft.

The set of generalised co-ordinates can usually be chosen in more than one way; normally it is most convenient to include in the set as many as possible of the displacements which are to be calculated, but it may be possible to simplify the working considerably by choosing some other set. By reason of the geometrical properties of the system, displacements of all points can be expressed in terms of the generalised co-ordinates.

4. Equations of Motion.

It is now possible to write down three expressions necessary for the derivation of the equations of motion. These are:

(i) the kinetic energy due to movements of the inertia elements;

(ii) the potential energy stored in the spring elements by deformations; and

(iii) the work done by the external applied forces.

Denoting these respectively by T, V and E, and a generalised co-ordinate by x, the equations of motion are obtained by applying Lagrange's equation in the form

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{x}}\right) - \frac{\partial T}{\partial x} + \frac{\partial V}{\partial x} = \frac{\partial E}{\partial x} \quad . \qquad (1)$$

once for each co-ordinate x. The second term on the left hand side of this equation is zero in most cases of engineering problems, as the kinetic energy is normally a homogeneous quadratic function of generalised *velocities* only.

The external applied forces to which corresponds the work function E are normally sinusoidal and of various frequencies. Since the response of all parts of the system to an applied sinusoidal force is sinusoidal and of the same frequency as the force, the work is simplified by invoking the principle of superposition: the total response to a combination of applied forces of different frequencies is the sum of the responses to the individual forces. In most practical cases of engineering importance in aircraft, the frequencies of the forces are directly proportional to the operating speed of the power plant, and for any given operating speed the forces can be divided into sets, the forces of each set having the same frequency. The response to each set is considered separately. A further simplification is achieved by splitting each force, if necessary, into two components: one in phase with, and one in quadrature with, a chosen phase-datum; these components are again considered separately.

For a system with n degrees of freedom there will be n generalised co-ordinates x_1, $x_2 - x_n$. The term $\partial E/\partial x_i$ on the right hand side of equation (1) is called the "generalised force" corresponding to the co-ordinate x_i, and is here denoted by P_i. In the simplifying procedure just outlined, all the forces included at any time will be of the form $P_i = F_i \sin wt$, and the deflections will also be of the form x_i

$= A_i \sin wt$, the frequency of vibration being $9.55w$ cycles per minute ;

Thus $x_i = -w^2 A_i \sin wt$, and the equations of motion can be put in the matrix form :

$$[C]\,[A] = [F] \quad . \quad . \quad (2$$

where the typical element C_{ij} of the matrix $[C]$ has the form $a_{ij} - b_{ij} w^2$.

5. Solution for Response.

If certain degrees of freedom are completely uncoupled from certain others, the equations (2) can be divided into two or more sets, no two sets containing any common co-ordinate. If this is the case, each set is solved separately in the same manner as in the general case discussed below, except that of course the value of n is correspondingly smaller.

Transposing in equation (2), the solution for the amplitudes A_i takes the form

$$[A] = [C]^{-1}[F]$$

If Y_{ij} is the cofactor of the typical element C_{ij} in the determinant $|C|$, then $[C]\,[Y] = |C|$, and

$$[A] = \frac{[Y]\,[F]}{|C|} \quad . \quad . \quad (3)$$

Any particular amplitude A_i can therefore be calculated from the corresponding equation in (3), and since both the matrix $[Y]$ and the determinant $|C|$ contain w the amplitude can be plotted as a function of the frequency.

Various special methods of solving the equations of motion have been derived for special purposes ; the procedure outlined above may be regarded as the straightforward way, which may be either more or less tedious according to the circumstances of the problem.

6. Dynamic Flexibility.

In some problems, particularly those connected with the vibrations of the aircraft power plant, it is desired to calculate only the response in one degree of freedom, corresponding to the motion at a connecting point between the system under consideration (e.g. the engine) and another system (e.g. the propeller). For this purpose the relevant displacement is denoted by one of the generalised co-ordinates, say X_L, and the value of X_L is calculated for the case in which the only external force is a corresponding force P_L of unit amplitude. Under these conditions the value of A_L, known as a dynamic flexibility, can be used as a linking parameter. It is the reciprocal of the more usual quantity "dynamic stiffness," the properties and uses of which the author has described elsewhere.*

It may be noted that operation of this technique involves the calculation of only one of the quantities $[A]$ in equations (3).

7. Natural modes.

The foregoing may be regarded as the mathematician's approach to the problem. The engineer desires a clearer mental picture of the situation than is offered by this straightforward analysis, and usually prefers to calculate in terms of natural modes, equilibrium amplitudes and dynamic magnifiers. The analysis can be extended to meet these requirements.

Solution of the equation $|C| = 0$ yields a number of roots in $Q = w^2$, corresponding to the natural frequencies of the system. In general there will be n real and distinct natural frequencies ; the unusual cases where some of the roots are equal will not be considered here. The n values of Q being denoted by Q_1, $Q_2 - Q_n$, for any root Q_r the relative magnitudes of the amplitudes A_i can be calculated, and together form what is known as the "r^{th} natural mode."

In these calculations it is customary to assign arbitrarily a unit value to one particular amplitude A_p (in the study of vibrations in engine crankshafts, this is frequently the amplitude at the free end)

* See Journal, November, 1941, January, 1943, and July, 1944; and also "Fundamentals of Vibration Study," Chapman & Hall, 1942.

and the ratio $X_i = A_i/A_p$ is termed the specific amplitude of x_i relative to x_p.

$$\text{Let } S_{pr} = \frac{\Sigma (X_j F_j)_r}{Q_r \Sigma\Sigma (b_{hk} X_h X_k)_r} \quad . \quad (4)$$

where the subscript "r" denotes that the expression is to be evaluated for $Q = Q_r$; and let

$$M_r = Q_r/(Q_r - Q) \quad . \quad (5)$$

Then it can be shown (see Appendix A) that

$$A_i = \sum_r (X_{ir} S_{pr} M_r) \quad . \quad (6)$$

The interpretation of this equation is as follows: A_i is the amplitude of the co-ordinate x_i at any frequency, to which corresponds the value of Q; X_{ir} is the specific amplitude of x_i relative to x_p in the r^{th} natural mode; S_{pr} is the equilibrium amplitude of x_p in this mode, and M_r is the dynamic magnifier for the mode. Thus the resultant amplitude of any co-ordinate is found by summing, for all the natural modes, the product of the equilibrium amplitude for that co-ordinate in the mode and the dynamic magnifier for the mode; and this equilibrium amplitude is the product of the equilibrium amplitude at some standard reference point and the specific amplitude relative to that point.

8. Equilibrium Amplitude.

In the case of torsional vibrations, the co-ordinates being the torsional displacements at the inertias, the values of b_{hk} are zero except along the leading diagonal of the matrix $[C]$, and $b_{hh} = J_h$ = inertia whose displacement is x_h. The expression (4) then simplifies to

$$S_{pr} = \frac{\Sigma (XF)_r}{Q_r \Sigma (JX^2)_r}$$

which is the equivalent of the standard form given by Ker Wilson*; in the work quoted the formula is based on a physical definition of equilibrium amplitude, as the amplitude at which the maximum kinetic energy (which equals the total vibrational energy in the system) would be equal to the work done by external forces in deflecting the system from the position of rest to an extreme position.

The general expression for the kinetic energy is, in the present notation,

$$T = \tfrac{1}{2} \Sigma\Sigma (b_{hk} \dot{x}_h \dot{x}_k).$$

The maximum value is therefore

$$\tfrac{1}{2} Q \Sigma\Sigma (b_{hk} A_h A_k) = \tfrac{1}{2} Q A_p^2 \Sigma\Sigma (b_{hk} X_h X_k).$$

The work done by the external forces in deflecting the system to an extreme position is

$$\tfrac{1}{2} \Sigma (FA) = \tfrac{1}{2} A_p \Sigma (XF).$$

By equating these two quantities and solving for A_p, the expression (4) for the equilibrium amplitude of x_p can be derived.

The proof of the formula (6), outlined in the Appendix, serves therefore to establish a rigorous mathematical justification for the common engineering method of analysis, which may be summarised thus:

(i) Find the natural frequencies.

(ii) Determine the mode at each natural frequency, one particular amplitude being arbitrarily assigned unit value and the others determined as specific amplitudes relative to it.

(iii) For any co-ordinate, determine its equilibrium amplitude in each mode as the product of its specific amplitude and the equilibrium amplitude of the reference co-ordinate.

(iv) For any co-ordinate the resultant amplitude is the sum, for all modes, of the product of its equilibrium amplitude and the dynamic magnifier for the mode.

9. Summary of Method (Formulae).

$x_1, x_2 \text{ —— } x_n$ are generalised (independent) co-ordinates defining the deflected configuration of the system.

* Ker Wilson, "Practical Solution of Torsional Vibration Problems," Chapman and Hall, 1942, Vol. I., p. 431.

T = kinetic energy $= \frac{1}{2} \Sigma\Sigma (b_{hk} \dot{x}_h \dot{x}_k)$

V = potential energy $= \frac{1}{2} \Sigma\Sigma (a_{hk} x_h x_k)$.

E = work done by external applied forces on deflections (see Appendix B).

Then Lagrange's equation

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{x}_i}\right) - \frac{\partial T}{\partial x_i} + \frac{\partial V}{\partial x_i} = \frac{\partial E}{\partial x_i} = P_i$$

yields the equations of motion in the form $[C][A] = [F]$ where $C_{ij} = a_{ij} - b_{ij} Q$, $Q = w^2$, $P_i = F_i \sin wt$, $x_i = A_i \sin wt$. The solution is $[A] = \dfrac{[Y][F]}{|C|}$, where Y_{ij} is the cofactor of C_{ij} in the determinant $|C|$.

Alternatively, let Q_1, Q_2 —— Q_n be the roots in Q of the equation $|C| = O$; choosing one co-ordinate x_p as reference, let $X_i = A_i/A_p$ (specific amplitude). For each mode ($Q = Q_r$), the dynamic magnifier is $M_r = Q_r/(Q_r - Q)$ and the equilibrium amplitude of x_p is

$$S_{pr} = \frac{\Sigma\ X_j F_j)_r}{Q_r\ \Sigma\Sigma\ (b_{hk} X_h X_k)_r}$$

Then

$$A_i = \sum_r (X_{ir} S_{pr} M_r).$$

10. Simple Example.

As a simple example, consider the system depicted in Fig. 1. It is desired to derive graphs showing the amplitudes of deflection in the two springs for a range of frequencies

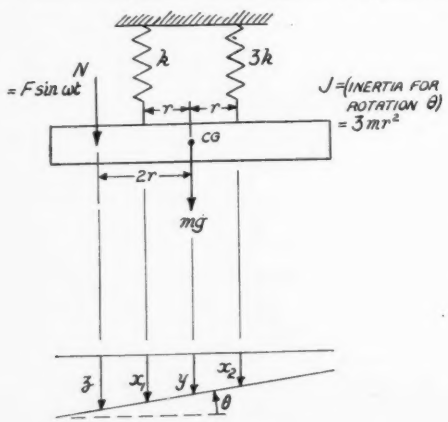

Fig. 1
Spring-suspended System.

of the applied force N. Two co-ordinates are required, the motion being supposed confined to vertical displacements and rotations in the plane of the diagram; these co-ordinates may be, for example, the deflections x_1 and x_2 in the springs, or the deflection y of the mass centre of the suspended body and the rotation θ about the mass centre. Since the response in the springs is required, this set of co-ordinates will be chosen.

Then

$T = m8\ [(\dot{x}_1 + \dot{x}_2)^2 + 3\ (\dot{x}_1 - \dot{x}_2)^2]$

$V = \frac{1}{2}k\ (x_1^2 + 3\ x_2^2)$

$E = Fz^2/2Z$, where $z = Z \sin wt = y + 2r\theta = \frac{1}{2}\ (3x_1 - x_2)$ (see Appendix B). In terms of amplitudes, the equations of motion become

$$\begin{bmatrix} k - Qm & \frac{1}{2}Qm \\ \frac{1}{2}Qm & 3k - Qm \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \end{bmatrix} = \frac{F}{2} \begin{bmatrix} 3 \\ -1 \end{bmatrix}$$

i.e.,

$$(k - Qm)\ A_1 + \tfrac{1}{2}\ QmA_2 = 3F/2$$
$$\tfrac{1}{2}QmA_1 + (3k - Qm)A_2 = -\ F/2$$

and, putting $L = Qm/k$,

$$\begin{bmatrix} A_1 \\ A_2 \end{bmatrix} = \frac{Fk \begin{bmatrix} 18 - 5L \\ -(2\ L \end{bmatrix}}{12 - 16L + 3L^2}$$

The graphs of A_1 and A_2 are plotted against frequency in Fig 2*a*.

In the second method of analysis, the roots of the equation $|C| = 0$, i.e., $3L^2 - 16L + 12 = 0$, are first found. The two roots are $L_1 = 0.9028$, $L_2 = 4.431$. Choosing x_1 as reference, $X_2 = A_2/A_1 = -\ (2 + L)/(18 - 5L)$ in each mode, and

$$S_1 = \frac{F\ (3 - X_2)}{2kL\ (1 - X_2 + X_2^2)}$$

in each mode. Thus in the first mode, $X_2 = -\ 0.2153$, $S_{11} = 1.411\ F/k$, and in the second mode $X_2 = 1.548$, $S_{12} = 0.0887\ F/k$. The expressions for the amplitudes are therefore

$$A_1 = \left(\frac{F}{k}\right)\ (H + K),$$

$$A_2 = \left(\frac{F}{k}\right)\ (-0.2153\ H + 1.548\ K)$$

where $H = \dfrac{1.411 \times 0.9028}{0.9028 - L}$,

$K = \dfrac{0.0887 \times 4.431}{4.431 - L}$

The separate components for each mode are shown in Fig. 2b. It will be found, of course, that the sum of the two components of each amplitude is the same as in Fig. 2a.

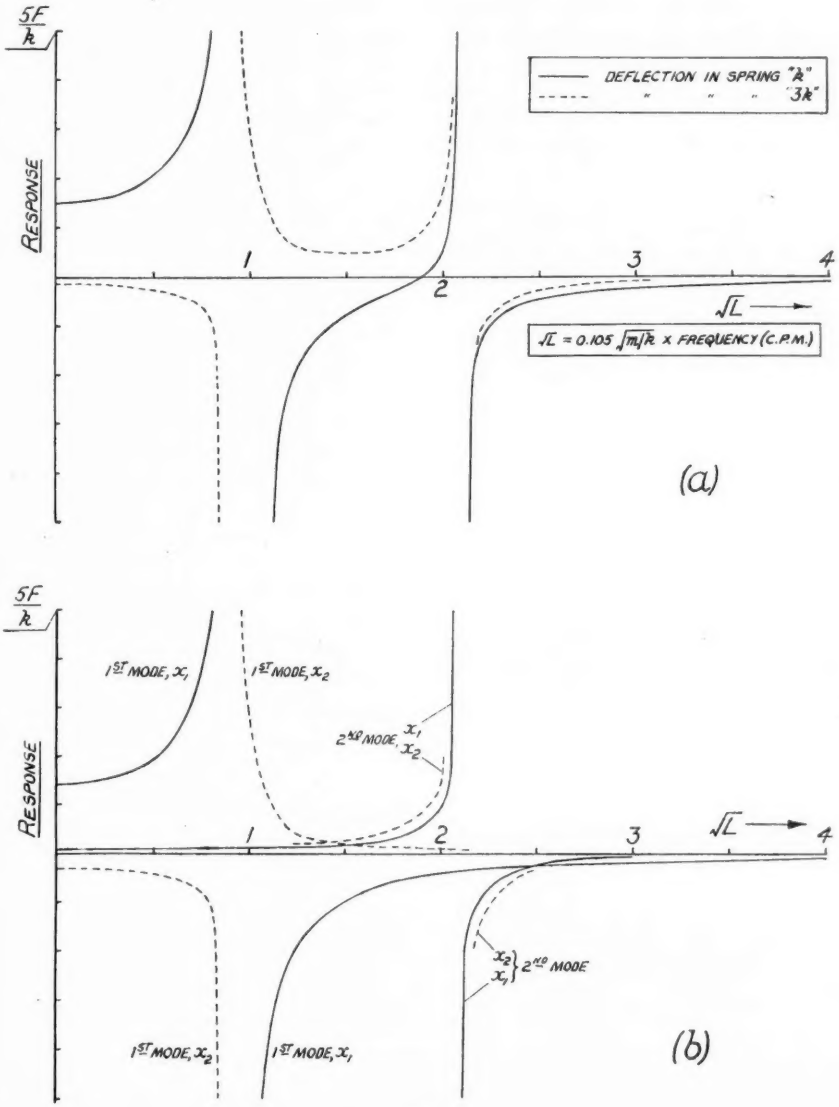

Fig. 2

(a) Response in Springs as Functions of Frequency.
(b) Modal Components of Response.

Appendix A. Outline Proof of Equation (6).

The full proof of this equation is too complicated to give in detail, but the following outline should enable the steps in the demonstration to be traced.

For natural free vibrations, the applied forces are all zero and so is the value of the determinant $|C|$. Moreover, for any root Q_r, $(x_i/x_p)_r = (Y_{ij}/Y_{ip})_r$ for any value $i = 1, 2 \text{ —— } n$, x_p being a particular co-ordinate selected arbitrarily as a reference. Thus $(Y_{ij})_r = (Y_{ip} X_j)_r$.

Since the equation $|C| = 0$ has n roots Q_r in Q, $|C|$ can be expressed in the form of a product,

$$|C| = k \prod_r (Q - Q_r)$$

where k is some constant. Consequently equation (3) can be expressed in the form of a sum of partial fractions,

$$[A] = \sum_r \left(\left(\frac{[Y]\,[F]}{\dfrac{|C|}{Q - Q_r}} \right)_r \frac{1}{Q - Q_r} \right).$$

Now the matrix product $[Y]_r\,[F] = [Y_{ip} X_j]_r\,[F]$ by reason of the relation proved in the preceding paragraph, and the i^{th} row is $(Y_{ip} \sum X_j F_j)_r$. Also, $Lt._{Q \to Q_r} |C| / Q - Q_r = - \sum\sum (b_{hk} Y_{hk})$ by L'Hospital's rule. Finally, $(Y_{hk} Y_{pp})_r = (Y_{ph} Y_{pk})_r$, or $(Y_{hk})_r = (Y_{ph} Y_{pk} / Y_{pp})_r = (Y_{pp} X_h X_k)_r = (Y_{ip} X_h X_k / X_i)_r$. On making the appropriate substitutions the equation (6) follows.

Appendix B. Note on Work done by external Forces.

The work done by a force N on a displacement z is $E = \int N.\, dx$. If $N = F \sin wt$, and $z = Z \sin wt$, then $N = Fx/z$ and $E = (F/2Z)z^2$. When z is a function (normally linear) of a number of co-ordinates x,

$$P_i = \frac{\partial E}{\partial x_i} = \frac{F}{Z} z \frac{\partial z}{\partial x_i},$$

and if $P_i = F_i \sin wt$, $F_i = F\, \partial z / \partial x_i$.

(When $z = x_i$, so that the point of application of the force is deflected through a distance measured directly by one of the generalised co-ordinates, $P_i = N$ and $F_i = F$.)

Nevertheless, the maximum work done by the applied force is $\frac{1}{2}FZ$, and not FZ, as can be seen by substituting Z for z in the expression just given. The physical significance of the factor $\frac{1}{2}$ is to be found in the fact that, since the phase difference between the force and the displacement is a multiple of 180°, the displacement is always directly proportional to the force, so that the area corresponding to the integral for work done is the area of a right-angled triangle, whose base is Z and whose height is F.

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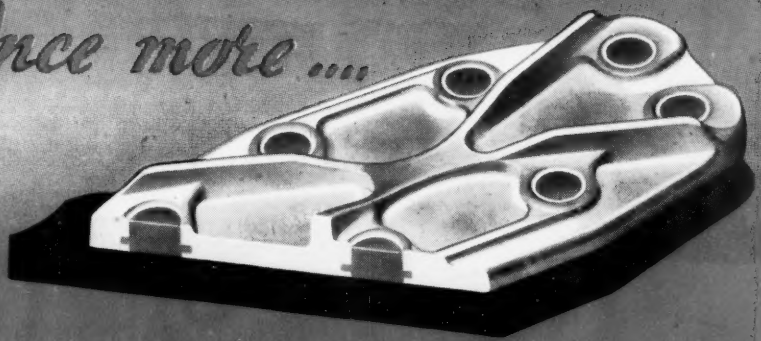

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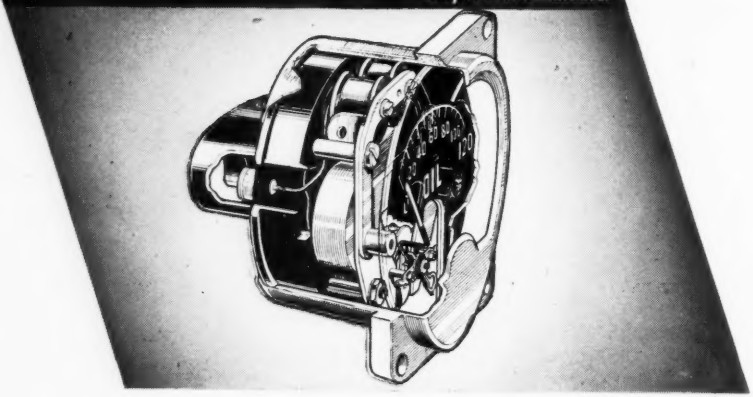
FEATURES OF WESTON AIRCRAFT INSTRUMENTS

No. 2
Temperature Indicator



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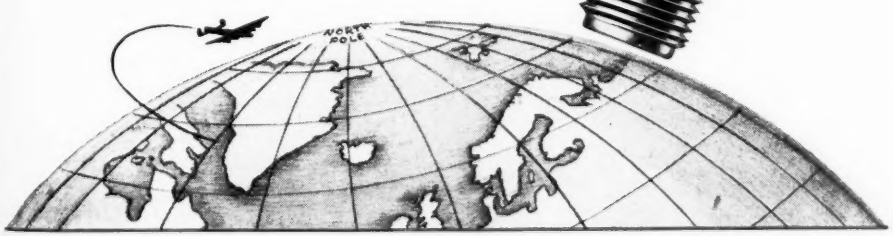

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